Evaluation of AI-assisted HAZOP Software Tools

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The Hazard and Operability (HAZOP) study is essential for identifying potential hazards in process industries. However, the development of HAZOP study is a complex and time-consuming process that requires supporting tools. HAZOP software tools automate various aspects of the HAZOP process, providing expert guidance to help companies identify hazards, develop and implement suitable safeguards, and streamline the process safety management. There is commercially available wide range of HAZOP software systems, each with distinct functionalities. This study analyzes 18 HAZOP software tools, focusing on their level of automation, time and cost efficiency, input requirements, generated output features, and artificial intelligence (AI) integration. Key challenges are identified, and a conceptual AI-Assisted HAZOP framework is proposed for addressing them. Through review and evaluation of software demos and demonstration sessions with software providers, the study examines features ranging from pre-built templates and customizable reports to advanced libraries of deviations, common failure modes, and consequences, as well as AI capabilities such as large language models (LLM), prompt engineering, and qualitative reasoning systems. Despite these advancements, challenges such as hallucination (the generation of incorrect or misleading outputs), reduced accuracy, time consumption, and high costs continue to hinder the effective automation of the HAZOP process. The findings highlight the need for AI-driven solutions with predictive capabilities to reduce manual input and enhance the accuracy of the hazard identification process. The conceptual framework leverages historical data from P&IDs and HAZOP reports to predict deviations, causes, consequences, safeguards, and recommendations for new projects, offering actionable insights for future HAZOP tool development to enhance safety outcomes in process industries.

Keywords: *HAZOP, Software tools, AI, LLMs, Prompt Engineering, qualitative reasoning system, Proposed framework.*

1. Introduction

Process industries, including oil and gas, chemical manufacturing, and petrochemicals, are complex and high-risk sectors where incidents like fires, explosions, equipment malfunctions or hazardous material releases can cause severe environmental and safety impacts (Solukloei et al., 2022; Zhang et al., 2023). Process hazard analysis (PHA) plays a crucial role in mitigating these hazards. The Hazard and Operability (HAZOP) study is a key PHA approach used to identify potential deviations from design intent, analyzing their causes, and consequences, and proposing necessary safeguards to mitigate hazards and enhance operational safety (Amin & Khan, 2022; Pasman et al., 2022). HAZOP analysis is based on meetings wherein a multidisciplinary team analyzes the hazards and operational issues. Initially, Piping and Instrumentation Diagrams (P&IDs) of a process are divided into distinct segments (nodes). Then each node is examined with brainstorming using a set of process parameters (e.g., flow, pressure, temperature, and level) and guide words (e.g., no, less, more, high, and low) to generate deviations (e.g., no flow, high pressure). Reasonable causes of deviation are identified for each node. The consequences associated with each cause are then discussed. The safeguards for each consequence are examined, and recommendations are presented as a layer of protection if required (Guo et al., 2021; Wang et al., 2023).

HAZOP study is a systematic and structured brainstorming which allows companies to reveal hazards and operational issues (Crawley & Tyler, 2015; Joubert et al., 2021). Personal insights and expertise can identify subtle problems that automated systems might overlooked. However, the traditional HAZOP study is finished when the team have found the causes of hazards, the consequences, and protection layers, which is time-consuming, and therefore expensive. It is often labor-intensive and heavily reliant on expert knowledge. The manual nature of data entry, guideword application, and report generation can significantly extend the time required to complete a thorough analysis (Baybutt, 2015). knowledge retention is at risk due to experts' retirement and staff turnover, and there is a strong bias in risk assessments based on human intuition. This method struggles with scalability and managing complex projects due to reliance on subjective judgment. Blind spots can occur, and documentation can be difficult to manage and follow up (Joubert et al., 2021).

In response to these challenges, companies in the process industries are increasingly turning to digital tools and AI-assisted technologies to streamline the HAZOP process, especially given concerns about staff turnover, expert retirements, and the recruitment of less experienced team members. Digital HAZOP solutions serve as valuable resources for new team members, helping them to build competencies and learn from historical data. These tools provide features that help HAZOP teams reduce the time, effort, and cost typically involved in traditional HAZOP studies. Additionally, Digital tools are essential for retaining valuable HAZOP knowledge, ensuring organized, accessible insights from past studies. They offer comprehensive support for complex projects, facilitate easy access to extensive documentation, and enable effective action tracking, which aids in managing identified hazards. Therefore, this study examines the functionalities of existing HAZOP software tools and explores their AI capabilities (detailed in sec. 3) that enable companies in process industries to enhance the efficiency and accuracy of HAZOP studies, making it a powerful tool to enhance hazard identification process and improve safety outcomes. The comparison between the traditional HAZOP versus digital HAZOP based on these identified criteria are illustrated in **Figure** 1.

Figure 1: Comparison of Traditional vs. Digital HAZOP Based on Key Criteria.

The literature review indicates that semi-automated tools have been developed to support aspects of the HAZOP study, including TORANAS (Mechhoud et al., 2016), PHAST 7.2 (Bouafia et al., 2020), ALBATROS III (Zenier & Antonello, 2023), and Stateflow (Chia & Naraharisetti, 2023) . For instance, (Chia & Naraharisetti, 2023) introduced a computer-aided tool called Stateflow for use in the oil and gas industry. This tool leveraged a knowledge base to identify causes of deviations across a wide range of processes in the HAZOP study. It begins by gathering raw data and information from process plant diagrams (Piping and Instrumentation Diagrams (P&IDs) and Process Flow Diagrams (PFDs)), alongside the expertise of HAZOP participants, to facilitate computer-aided automation. A specific protocol and data structure were implemented to convert textual information into a format that the software could recognize and manipulate. In the next stage, the knowledge base was managed, organizing deviations and their associated industrial causes and consequences into a structured database library. Once this library was established, the digital representation of the process plant data was created using Stateflow's graphical interface. This involved designing units or blocks that embedded decision logic, algorithms, and reasoning methods to computationally generate HAZOP outputs. The final stage converted these outputs back into qualitative expressions in the form of a HAZOP worksheet, completing the automation process. However, certain limitations remain, such as challenges with the quality of output data and the manual effort required to build the knowledge database. Additionally, the exclusion of causes like operational errors and equipment maintenance, as well as the absence of consequences and recommendations, renders the knowledge base insufficient for more complex plants. (Zenier & Antonello, 2023) proposed the ALBATROS III software to reduce wasted time by processing Fault Trees and Minimal Cut Sets (MCS) within the context of HAZOP applications. ALBATROS III used MS Excel worksheets to facilitate HAZOP documentation, as well as Fault Tree development and MCS reporting. While the HAZOP methodology followed classical criteria, it employed unique codes linked to primary event descriptors. The software provided users with predefined guide words for HAZOP studies, which can be customized, offering flexibility in qualifying deviations. However, the reliance on MS Excel worksheets for HAZOP documentation may present challenges in large-scale plants with extensive data, as it could increase complexity. Additionally, the HAZOP worksheet is divided into parameters, causes, and effects, while safeguards and recommendations are excluded, limiting the comprehensiveness of the analysis.

Despite the advances these tools represent, no commercial software tools have been released that apply these computer-aided approaches across a broad range of industries, limiting their practical application in the wider process industry. This research aims to evaluate the AI-assisted HAZOP software tools currently available in the market. It seeks to identify the functionalities of these tools, their capabilities, and limitations, as well as proposed recommendations to address the challenges faced by industry professionals when implementing these solutions. The structure of this paper is as follows: Section 2 presents the review methodology, with a particular emphasis on AI-based HAZOP tools, identifying their key features and potential applications.

Section 3 discusses the advantages and limitations of these tools and introduces a hybrid framework to overcome existing limitations and improve the efficiency and accuracy of AI-assisted HAZOP studies.

2. HAZOP Software Review Methodology

To conduct a thorough evaluation of HAZOP software tools, I actively engaged with the providers of 18 different platforms through demo sessions, trials, webinars, and direct discussions with product managers, developers, and process safety engineers. This allowed me to explore the required inputs, understand the procedures involved in conducting HAZOP, and assess each tool's cost, time efficiency, and AI capabilities. Moreover, user feedback and potential limitations were carefully considered. Based on this extensive review and the identified criteria, the tools were categorized into three groups: Template-based software, which offers pre-built formats for HAZOP studies; Library-based software, which leverages extensive libraries of guidewords, parameters, causes, and consequences; and AI-based software, which integrates artificial intelligence techniques to assist with automation of the HAZOP process. **Figure 2** shows the software tools in each category. These categories and their specific details will be discussed in the next sections to provide a deeper understanding of each tool's functionality and suitability for various HAZOP applications.

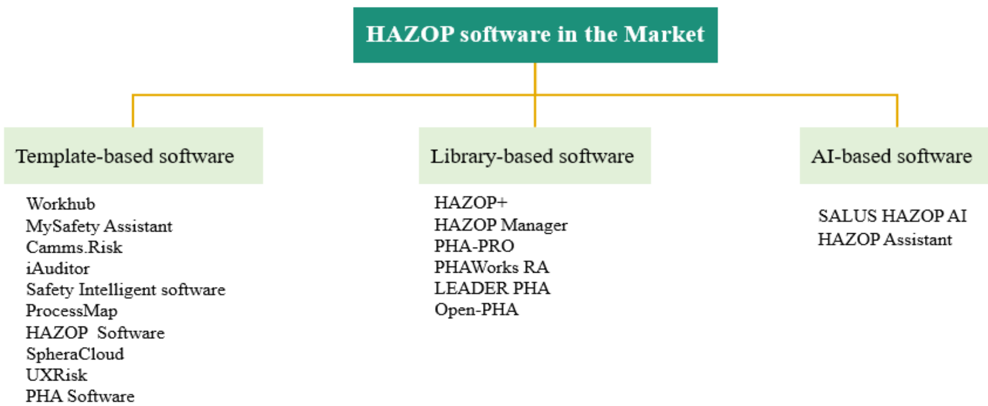

Figure 2: Classification of HAZOP Software Tools in the Market.

2.1. Template-based HAZOP software.

Template-based HAZOP software provides pre-built formats and customizable templates to streamline the HAZOP study process. These tools are designed to assist users by offering predefined fields and structures for entering data related to guidewords, deviations, causes, and consequences. While they simplify the initial setup and ensure a degree of consistency in report generation, these tools often rely heavily on manual data entry and human judgment for risk analysis and decision-making. As a result, they can be less efficient when dealing with complex or large-scale projects. Although template-based software is relatively easy to use and implement, its lack of automation and AI capabilities makes it more suited for organizations seeking straightforward solutions for storing and organizing HAZOP-related information with minimal customization. These tools may fall short when it comes to supporting more sophisticated, data-driven risk assessments.

As shown in **Figure 2**, ten software tools in this category are currently available in the market, serving primarily as customizable report templates for organizing and storing information during HAZOP studies. It is important to note that the storage capabilities of template-based software are generally limited compared to more advanced solutions. These tools focus on storing and organizing information in a structured format, rather than offering features like data analysis, automated risk identification, or AI integration. The emphasis remains on providing a user-friendly interface that facilitates efficient collection and retrieval of HAZOP data.

2.2. Library-based HAZOP software

Library-based HAZOP software builds upon the foundation of template-based tools by incorporating extensive libraries of predefined guidewords, deviations, causes, and scenarios that streamline the HAZOP process. These libraries serve as a comprehensive knowledge base, offering users the ability to reference and apply a wide range of industry-standard safety terms and risk scenarios during HAZOP studies. This significantly enhances the efficiency and consistency of hazard identification and risk assessment processes, as users can draw from an established set of parameters rather than manually inputting each detail. The capabilities and limitations of six library-based software tools are demonstrated in **Table 1**.

Table 1: Key Features and Limitations of HAZOP Software Tools in the Market.

Software	Developer	Cost	Target Industry	Capabilities	Limitations	Deployment
HAZOP +	Isograph 1986, United Kingdom,	$1,681.50 per year.	Oil and Gas, and Chemical Industry.	• Customizing, recording, and managing HAZOP studies. • Guiding users in identifying possible deviations using libraries of guidewords and parameters. • Incorporating risk ranking matrices to assess the likelihood and severity of each identified hazard. • Linking nodes to process diagrams for better visualization. • Logging meetings and enabling action assignment and tracking.	• Relying heavily on experts, making the process time-consuming and subjective. • On-premise operation limits flexibility, scalability, and remote access compared to cloud-based solutions. • Lacking AI-driven analytics or machine learning capabilities to analyze historical data and make predictive recommendations based on trends.	On-premise
HAZOP Manager	LihouTech 1985, United Kingdom	CAD 1660	Oil and Gas, Chemical, and pharmaceutical industry.	• Recording and managing all study stages, from preparation to completion. • Providing a database of causes and typical deviations based on primary (parameters) and secondary (guidewords) keywords. • Offering access to materials such as historical problems and failure rate data. • Enabling input of action classification codes for management reports.	• Depending entirely on experts, making the HAZOP process time consuming and subjective. • Requiring more training to use all the features effectively. • Offering limited customization compared to other adaptable HAZOP software. • On-premise operation limits flexibility, scalability, and remote access.	On-premise
PHA-PRO	Sphera 1978, United States	Not provided	Chemical process industry	• Providing preformatted standard PHA templates. • Including guidewords and parameters libraries for a systematic HAZOP study. • Offering a customizable risk matrix for ranking risks by likelihood and severity. • Integrating LOPA for quantitative analysis of high-risk scenarios.	• Users need to manually input data for each deviation, cause, and consequence, which can be time-consuming. • Lacking AI-driven analytics or machine learning capabilities to analyze historical data and make predictive recommendations based on trends	On-premise
PHAWorks RA Edition	Primatech Inc 1987 United States	$8,275 per user +$1400 annual fee	Chemical process industry	• Performing various PHA methods, including HAZOP, LOPA, FMEA, What-If analysis and checklist. • Providing flexibility for user customization of interface, study formats, and reports • Including guidewords and parameters libraries, risk matrix, and LOPA integration.	• Users need to manually input data for each deviation, cause, and consequence, which can be time-consuming. • Lacking AI-driven analytics or machine learning capabilities to analyze historical data and make predictive recommendations based on trends.	On-premise
LEADER PHA	ABS Group 1971, United States.	$4,400 per user	Oil & Gas, Chemical industry	• Conducting and documenting PHAs using HAZOP, What-if, FMEA, LOPA and other hazard evaluation techniques. • Using standard guidewords to identify potential deviations. • Providing customizable risk matrices to rank hazards by likelihood and severity. • Allowing users to upload P&ID files (PDF or image files) to represent the process layout. • Marking and annotating P&ID to indicate hazards, equipment failures, or deviations identified in the HAZOP study.	• Depending on experts during the entire HAZOP process. • Lacking flexibility and scalability of fully cloud-based solutions for remote access. • Limited template customization for broader risk management tasks compared to platforms like Camms.Risk. • Offering less advanced analytics, dashboards and data visualization than tools like SpheraCloud or PHAWorks RA Edition.	On-premise (spreadsheet-like)
Open-PHA	Kenexis 2004, United States	$2,250 per year	Chemical process industry	• Providing pre-built Template for HAZOP and LOPA studies, including Risk Matrix. • Using an integrated JSON data structure to enhance PHA documentation. • Offering reusable libraries of causes and safeguards. • Supporting bowtie visualization of scenarios in the cloud version.	• Requiring manual data input for each deviation, cause, and consequence, which can be time-consuming. • Lacking AI-driven analytics or machine learning capabilities to analyze historical data and provide predictive recommendations. • Still time consuming.	Cloud-based, On-premise

One of the key advantages of library-based software is its ability to provide structured libraries that facilitate the exploration of diverse scenarios, previously identified problems, failure rate data and other such historical information, including less obvious risks. This supports consistency across studies, enabling teams to reuse information from previous HAZOP sessions. Another advantage is that some software in this category enable users to mark, highlight, or annotate P&ID areas to indicate key hazards, equipment failures, or potential deviations identified during the HAZOP study. Moreover, such software also offers a powerful report generator for the creation and printing of professional quality reports and offers a project wizard to simplify creation of new projects.

While these tools are efficient in reducing manual input and ensuring consistency, they often still rely on user expertise to interpret and apply the libraries effectively. The tools do not typically incorporate advanced AI-driven analytics or predictive modeling, meaning that they still depend on human judgment for critical decision-making. Consequently, they do not proactively identify new risks or hazards beyond what has been stored. As a result, companies are seeking AI-enhanced solutions that can help HAZOP teams by predicting hazards, identifying their root causes more efficiently, and ultimately reducing the time required to conduct a HAZOP study.

2.3. AI-based HAZOP software.

Hybrid HAZOP approaches combine traditional HAZOP methodology with advanced technologies like artificial intelligence (AI) to enhance the efficiency and depth of hazard identification. AI-assisted HAZOP tools are designed to support, rather than replace, the learning opportunities inherent in traditional HAZOP, especially for less experienced practitioners. Limited number of HAZOP tools have been found in this category (only two tools). Software tools, including SALUS HAZOP AI and Kairos HAZOP Assistant, exemplify this approach by integrating conventional HAZOP processes with AI capabilities. SALUS HAZOP AI utilizes large language models (LLMs) and prompt engineering to automate incident retrieval and guide users through the HAZOP process, while Kairos HAZOP Assistant blends multiple methodologies such as multilevel functional model (MFM), HAZOP, failure mode, effect, and criticality analysis (FMEA), and qualitative reasoning system to create detailed flow models for equipment on P&IDs. These hybrid systems aim to reduce manual effort, streamline data entry, and incorporate AI-driven insights for more comprehensive risk analysis, though each tool varies in the extent of automation and process-specific adaptability. The functionalities and Limitations of AI based HAZOP software are illustrated in **Table 2**.

Table 2: AI-based HAZOP Software tools and their functionalities and Limitations.

Software	Provider	Cost	Input requirement	Output	Users feedback	Limitations
HAZOP AI	SALUS, Scotland.	Free of charge	Process and equipment descriptions of a node.	3 pipelines (relevant incidents, questions to be raised, and pre-populated HAZOP table).	• Needs graphical P&IDs. • Hallucination issue. • Accuracy issue.	• Manual input is cumbersome. • Accuracy reduced when deviating from provided examples. • Lacking a risk matrix and a library of safeguards and recommendations. • Better suited for smaller scopes rather than larger scale projects.
HAZOP Assistant	KairosTech and Vysus Group, Norway.	Starting from 5000 USD/Month based on the number of users.	P&IDs, equipment details, and access to libraries.	HAZOP report, annotated P&IDs, and tree view show failure propagation to Consequence.	• Generally positive, allowing teams to focus on higher-value tasks rather than manual data entry. • still requires experienced personnel to interpret complex scenarios. • needs quantitative assessment.	• Working on each piece of equipment rather than nodes. • Time consuming due to workshops. • High cost. • Risk of human error and bias in risk assessment. • The qualitative reasoning system lacks learning capabilities.

2.3.1. SALUS HAZOP AI

SALUS HAZOP AI software was developed by Salus Technical, a process safety firm based in Aberdeen, Scotland, utilizing large language models (LLMs) and prompt engineering to streamline the HAZOP study process by automating information retrieval and hazard identification. Users input process and equipment descriptions manually, and the AI uses these prompts to perform keyword and vector searches across an internal database of past incidents and best practices. The LLM then generates relevant incidents, questions, and suggestions to guide participants through the HAZOP study. **Figure 3** illustrates how SALUS HAZOP AI functions to generate three key pipelines to assist team members in conducting the HAZOP study.

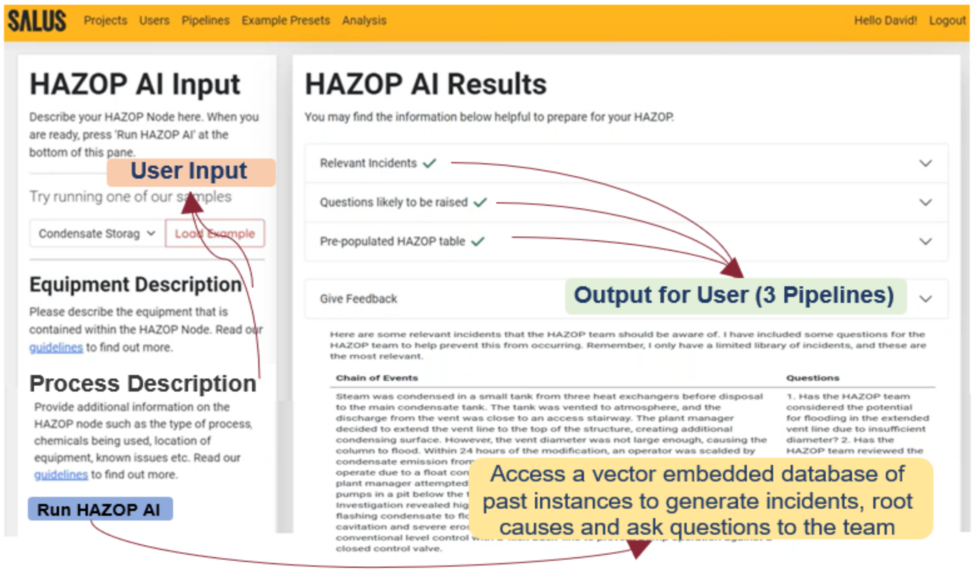

Figure 3: SALUS HAZOP AI Interface and its functions (adapted from the software (Salus Technical, 2023)).

While this approach helps structure the process, its reliance on a limited library and its focus on specific processes, like oil refineries, limits broader applicability. According to the software's founder "David Jamieson", after over 150 people signed up for trials and 70 companies booked demos, user feedback suggested that the tool should shift toward more graphical inputs for better reading and understanding of P&IDs. Users found manual input of process and equipment descriptions cumbersome, with accuracy diminishing when deviating from provided examples. Another challenge is the issue of hallucination, where the AI model generates inaccurate information, potentially undermining the reliability of the system's output. Hallucination occurs when a model guesses details or invents incidents that were not derived from actual data. For example, an AI model might produce recommendations or incident scenarios that appear plausible but lack a factual basis, as they are not supported by real training data or validated expert knowledge. This can result in misleading outcomes in HAZOP studies, leading to a lack of trust in the AI's recommendations. Additionally, the software lacks a risk ranking matrix and a library of safeguards and recommendations. It was also noted that the software is better suited for smaller work scopes rather than larger, more complex projects. As a result, development on this software was halted. Therefore, future improvements, including AI integration, advanced predictive models, and enhanced P&ID integration, should be considered.

2.3.2. Kairos HAZOP Assistant

HAZOP Assistant, developed by Kairos Technology in Norway, is a model-based software designed to streamline and enhance the hazard identification process. It leverages deterministic modelling of the plant, combined with deviation propagation analysis and artificial intelligence. It integrates multiple methodologies, including Hazard and Operability (HAZOP), Functional Model (MFM), and Failure Modes, Effects, and Criticality Analysis (FMECA). This hybrid approach utilizes libraries of equipment, deviations, failure modes, and consequences based on the API RP 14(C) standard (American Petroleum Institute., 2007) and DEXPI P&ID specification (DEXPI Initiative, 2021), reducing the need for manual input and ensuring consistent and thorough risk assessments. It allows users to utilize functional models of common equipment in the process industry or create custom MFMs for specific equipment not in the library, including detailed mass and energy flow diagrams for each piece of equipment on Piping & Instrumentation Diagrams (P&IDs). The software uses tag recognition to identify components on P&IDs and automatically links equipment with deviations, failure modes and their associated consequences in the database, offering a comprehensive analysis of potential risks. The software uses a qualitative reasoning technique that can search through its internal database of past incidents and highlight similar scenarios, their causes, and consequences. It also evaluates the likelihood and severity of each failure mode and consequences using risk matrix qualitatively. **Figure 4** shows the main components of this software.

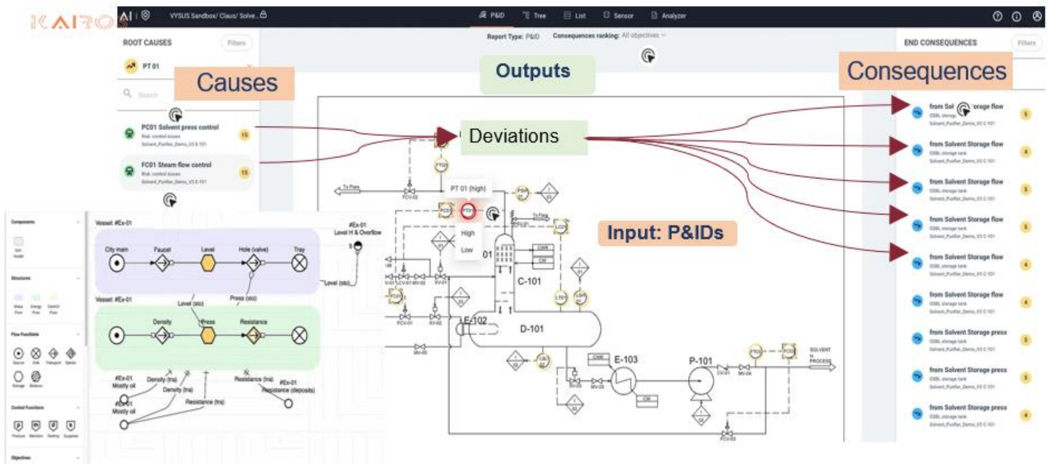

Figure 4: The main features of Kairostech HAZOP Assistant software (adapted from the software (KairosTech Technology, 2021)).

While HAZOP Assistant provides these functionalities, it still requires significant personal time and resources due to workshops. It works on each single equipment or instrumentation instead of nodes as a small section or specific area in P&IDs. The qualitative reasoning system relies on heuristic rules, which may need to be adjusted or expanded in response to minor variations in P&ID diagrams. While useful for hazard assessments, these qualitative methods can introduce subjectivity and lack the precision required for quantitative risk analysis, which is essential for accurately prioritizing risks. Additionally, creating functional models for each piece of equipment, considering varying operational conditions and detail levels, becomes time-consuming and challenging in large-scale projects. Moreover, the effectiveness of the tool's qualitative reasoning system relies heavily on the quality and scope of its knowledge. A limited database of past incidents, failure modes, or system knowledge can result in missed hazards or irrelevant recommendations. Furthermore, the system lacks adaptive learning capabilities, unlike machine learning-based systems that evolve and improve with continued use and new data.

3. Discussion and Proposed Conceptual AI-Assisted HAZOP Framework

After reviewing functionalities of HAZOP software tools, it is evident that several shared features are present across the market. These tools typically offer customizable risk matrices, guidewords, and parameters libraries, which aid in systematic HAZOP study. Additionally, many solutions integrate LOPA to provide more quantitative hazard evaluations. Most platforms support the generation of HAZOP reports and action tracking to ensure that recommendations are followed up on. However, a major drawback across many tools is the reliance on manual data entry, which is time-consuming and subjective. Another common limitation is the lack of AI-driven analytics or machine learning capabilities to automatically analyze historical data and make predictive recommendations. This absence of automation in identifying deviations and suggesting safeguards leads to a prolonged and expert-dependent HAZOP process.

AI-based HAZOP software tools integrate AI technologies into the traditional HAZOP process to improve efficiency and safety in hazard analysis process. These tools significantly reduce the need for expert intervention while cutting down the time and cost associated with HAZOP studies. However, a notable drawback is that they experience hallucination issues, undermining trust in the system's output by causing the AI model to generate inaccurate incidents or infer details not grounded in actual data. Therefore, integrating LLMs and prompt engineering with knowledge graph of P&IDs and vector-embedded databases would enhance the AI's ability to interpret, understand, and predict incidents more accurately. Accuracy remains a concern, especially when deviating from provided scenarios that the AI has not been trained on, which can lead to erroneous risk assessments. Users found the manual input of process descriptions and equipment descriptions for each node in P&IDs cumbersome and time-consuming. Additionally, the qualitative reasoning system lacks learning capabilities. Moreover, the absence of robust predictive capabilities based on historical training data further hampers the AI's potential to anticipate future hazards. Another limitation is the significant resource and time investment required to individually create functional models for each piece of equipment due to varying operational conditions, which makes scaling AI-driven HAZOP studies difficult, especially for large or complex facilities. These limitations highlight the need for ongoing improvements in AI-based HAZOP tools to fully realize their potential in automating and enhancing safety processes.

To address these challenges, a new conceptual AI-Assisted HAZOP framework is proposed. In this hybrid approach, the process begins with the HAZOP team examining P&IDs and associated technical data to break down the system into smaller, manageable nodes. The nodes serve as the input for the AI-Assisted HAZOP tool. Each node is annotated and linked to its corresponding technical information, then subjected to image preprocessing. Computer vision (CV) techniques, such as Mask-RCNN or YOLO are applied to identify relevant features from the P&ID images, generating detected objects and spatial information for further analysis. Simultaneously, a large language model (LMM), such as Gemini, is used with prompts to extract process description for each node. Both the detected objects from the images and the embeddings from the text descriptions are combined to create a comprehensive feature set, which is fine-tuned to improve efficiency. This combined data is then used to reverse the NLP process for generating HAZOP-related text, including deviations, root causes, consequences, countermeasures, and risk levels. All relevant data—such as P&IDs, node descriptions, and HAZOP reports—is stored in a central database, where it undergoes annotation and is structured for machine learning purposes. The model is trained on historical data to improve the prediction of HAZOP elements. Once trained, the model generates a complete HAZOP report, which is reviewed and audited by experts before it is used for operational decision-making. This system aims to streamline the HAZOP process by automating the generation of essential HAZOP elements and reducing manual effort, while ensuring that the data is continuously improved through feedback and training loops. Figure 5 illustrate the proposed framework for developing an intelligent HAZOP tool.

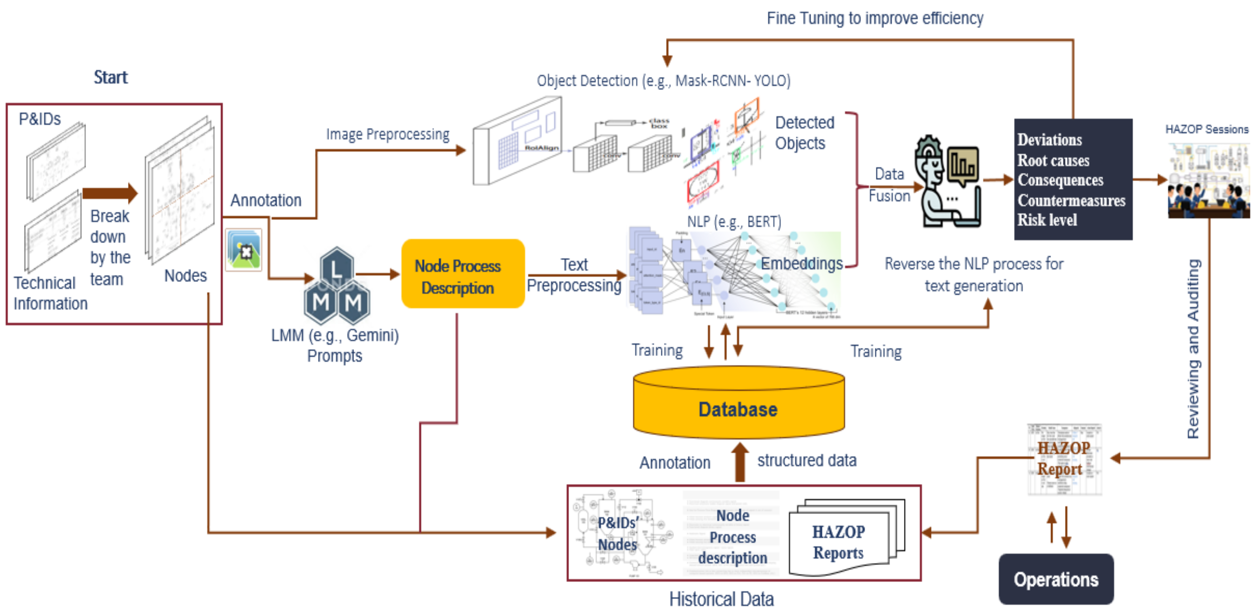

Figure 5: A proposed framework for an Intelligent HAZOP Tool.

4. Conclusion

Developing a HAZOP study is often complex and time-intensive, requiring supportive tools. Digital HAZOP tools can assist in speeding up the process of conducting HAZOP studies and reduce time spent in workshop sessions. This review identified 18 HAZOP software tools currently available in the market and classified them into three distinct categories**:** template-based tools**,** library-based tools, and AI-based tools. While the majority of the tools rely on templates and extensive libraries, AI-based HAZOP tools are limited with only two notable solutions integrating advanced AI capabilities. These AI-based tools significantly reduce the reliance on expert input while minimizing the time and cost involved in conducting HAZOP studies. However, they still face several challenges, such as hallucination issues**,** reduced accuracy when facing scenarios not covered in their training data, and time consumption when analyzing each piece of equipment across P&IDs. Moreover, they lack robust prediction capabilities and are limited by their inability to integrate graphical representations of P&IDs. To overcome these limitations, this study proposes a conceptual AI-Assisted HAZOP framework that leverages historical data from P&IDs and HAZOP reports. It includes integrating computer vision, large language models, and large multimodal models to process P&IDs' nodes, node process descriptions, and HAZOP reports. By training an AI model on this historical data, the tool would be able to predict deviations, causes, consequences, and countermeasures for new projects based on their P&IDs' nodes. The outputs generated by the model could then be reviewed and validated by the HAZOP team before being implemented in operations. By addressing the current shortcomings of AI-based tools, this approach could pave the way for more advanced and scalable solutions in hazard analysis process.

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