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Review

Hazard and operability (HAZOP) analysis. A literature review

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ABSTRACT

Hazard and operability (HAZOP) methodology is a Process Hazard Analysis (PHA) technique used worldwide for studying not only the hazards of a system, but also its operability problems, by exploring the effects of any deviations from design conditions. Our paper is the first HAZOP review intended to gather HAZOP-related literature from books, guidelines, standards, major journals, and conference proceedings, with the purpose of classifying the research conducted over the years and define the HAZOP state-of-the-art.

Contents

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1. Introduction

Identifying hazards is fundamental for ensuring the safe design and operation of a system in process plants and other facilities. Several techniques are available to identify hazardous situations, all of which require their rigorous, thorough, and systematic application by a multidisciplinary team of experts. Success rests upon first identifying and subsequently analyzing possible scenarios that can cause accidents with different degrees of severity. Without a structured identification system, hazards can be overlooked, so entailing incomplete risk-evaluations and potential loss. Annex III of the SEVESO Directive stresses the importance of adopting and implementing procedures to systematically identify major hazards arising from normal – and abnormal – operations, and to assess their likelihood and severity [1].

Reviews of Process Hazard Analyses (PHA) include a report of the U.K. Health and Safety Laboratory [2], and two books [3,4] that discuss the purposes, execution methodologies, advantages, and limitations of the most often used PHA techniques. Our review focuses on one of these PHA techniques, hazard and operability (HAZOP) analysis, and defines the state of knowledge and potential for improving this important methodology.

A HAZOP study is a highly disciplined procedure meant to identify how a process may deviate from its design intent. It is defined as the application of a formal, systematic critical examination of the process and the engineering intentions of new or existing facilities to assess the potential for malfunctioning of individual pieces of equipment, and the consequential effects on the facility as a whole. Its success lies in the strength of that methodology in following a system's Process Flow Diagrams (PFDs) and Piping and Instrumentation Diagrams (P&IDs), breaking the design into manageable sections with definite boundaries called nodes, so ensuring the analysis of each piece of equipment in the process. A small multi-disciplinary team undertakes the analysis, whose members should have sufficient experience and knowledge to answer most questions on the spot. The members are selected carefully, and are given the authority to recommend any needed changes in design.

Executing the method relies on using guidewords (such as, no, more, less) combined with process parameters (e.g., temperature, flow, pressure) that aim to reveal deviations (such as less flow, more temperature) of the process intention or normal operation. This procedure is applied in a particular node, viz., as a part of the system characterized for a nominal intention of the operative parameters. Having determined the deviations, the expert team explores their feasible causes and their possible consequences. For every pair of cause-consequence, safeguards must be identified that could prevent, detect, control, or mitigate the hazardous situation. Finally, if the safeguards are insufficient to solve the problem, offering recommendations must be considered.

The concept of a HAZOP study first appeared with the aim of identifying possible hazards present in facilities that manage highly hazardous materials. The purpose was to eliminate any source leading to major accidents, such as toxic releases, explosions, and fires. However, over the years, HAZOP's application readily extended to other types of facilities because of its success in identifying not only hazards, but also operational problems. Thus, HAZOP was adopted for medical diagnostic systems [5], road-safety measures [6], and hazard analysis in photovoltaic facilities [7], among others. This diversity of usage illustrates how HAZOP has become considered as a powerful technique to improve many kinds of systems. In this sense, we found it necessary to limit the scope of our paper to considering the evolution of HAZOP research from its starting point to the present day on issues about chemical processes, accounting for the US Occupational Safety and Health Administration (OSHA) Process Safety Management Rule (PSM) and the SEVESO Directive.

Table 1
Sources of most published papers.

Source	Number
Computers & Chemical Engineering	17
Journal of Loss Prevention in Process Industries	15
Reliability Engineering & System Safety	14
Process Safety Progress	10
Chemical Engineering Progress	8
IEEE Transactions on Reliability	6
Professional Safety	5
AIChE Journal	4
Hydrocarbon Processing	4
ISA Transactions	4
Journal of Hazardous Materials	4
Plant/Operations Progress	3
Safety Science	3
Industrial and Engineering Chemistry Research	2
Nuclear Engineering and Design	2
Accident Analysis & Prevention	1
AIChE Symposium Series	1
Chemical Engineering Science	1
Computer methods and Programs in Biomedicine	1
Environmental Modeling & Software	1
Expert Systems with Applications	1
Gas Separation & Purification	1
IEE Colloquium on Hazards Analysis	1
International Journal Hydrogen Energy	1
Korean Journal of Chemical Engineering	1
Process Safety and Environmental Protection	1
Quality and reliability engineering international	1
Tsinghua Science and Technology	1

2. Published literature

2.1. Scope of the current review

Our aim was to review much of the existing literature on HAZOP studies to identify the current state-of-the-art. Our review starts by summarizing the main ideas in 166 published studies, classifying the publications in several groups, and expanding their particular features independently in the next section. Thereafter, we discuss the collected information, and draw conclusions after defining the HAZOP state-of-the-art.

HAZOP is the focus of much research aimed at improving the safety of chemical plants that increasingly operate at higher temperatures and pressures, and encompass more complex, sophisticated processes. We collected the information mainly from publications in major journals and conference proceedings (Tables 1 and 2), but also from books, guidelines, and standards. The period we covered is from its starting point in 1974 with the

Table 2
Conference proceedings sources.

International Conference on Human Factors in Control Rooms
Annual Conference into the Major Safety, Reliability and Risk Analysis—ESREL
Annual Conference of the Society of Maintenance and Reliability Professionals
Annual Conference on Systems Integrity, Software Safety and Process Security
Conference and Workshop on Reliability and Risk Management
IEE Colloquium on Hazards Analysis
IEE Colloquium on Model Building Aids for Dynamics System Simulation
IEEE International Conference on Computational Cybernetics
International Conference on Systems, Man and Cybernetics
International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems
International Conference on Probabilistic Safety Assessment and Management—PSAM
International Process Plants Reliability Conference and Exhibition
International Symposium Loss Prevention and Safety Promotion in the process Industries Loss Prevention
International Workshop on Artificial Intelligence for Industrial Applications
Risk Management and Critical Protective Systems: Proceedings of SARSS
Safety Critical Systems Symposium

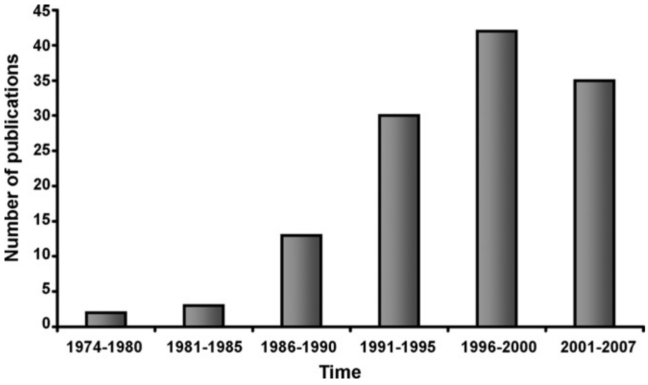

Fig. 1. Trend of related-HAZOP publications.

first publication of work carried out by Lawley [8], up to the present. The number of published studies gradually rose over the years from 1974 until 1997–1998, the period with the maximum number of publications. Over the three decades of HAZOP improvements, 60% of the research occurred from 1990 to 2000 (Fig. 1); further, most of this work concerns the development of expert systems intended to automate HAZOP (Fig. 2).

Many different viewpoints have been advanced on improvements in HAZOP, from extending its execution in several technological fields, to its automation by developing expert systems. As shown in Table 3, we aggregated the reviewed literature into six research topics that we deemed a sufficiently detailed classification for undertaking a global view of HAZOP. However, other particular topics within each main research line may be expanded easily, as we will show in the next section.

We found it instructive and interesting to specify the starting point of the HAZOP and its continuous progress over the years to the present, highlighting its success and consolidation as the most systematic, rigorous, thorough, and universally used hazard-identification technique.

2.2. *The evolution of HAZOP*

HAZOP studies evolved from the Imperial Chemical Industries' "Critical Examination" technique formulated in the mid 1960s. One decade later, HAZOP was published formally as a disciplined procedure to identify deviations from the design intent. Lawley [8] defined and delineated the principles needed to carry out operability studies and hazard analysis due to the increasing complexity of new processes that could not be examined thoroughly using the then-conventional approaches based on equipment-oriented practices. Indeed, the requirement for having process-oriented methods of examination was the reason for the generation of HAZOP. Lawley's paper defines the planning, execution, and treatment of the operability study. Two years later [9], he specified the technical – and managerial – principles underlying HAZOP studies, and detailed the factors that had to be taken into account to develop the HAZOP successfully. The planning of the study, the skills of the leader, the study procedure, the evaluation of potential problems, and the process of considering the changes proposed in the analyzed units were set out carefully. Moreover, he gave new examples of the study to illustrate how HAZOP worked. Just one year later, the Chemical Industries Association in the U.K. published the first guideline to HAZOP, as a technique used in the process industries for identifying hazards and planning safety measures [10].

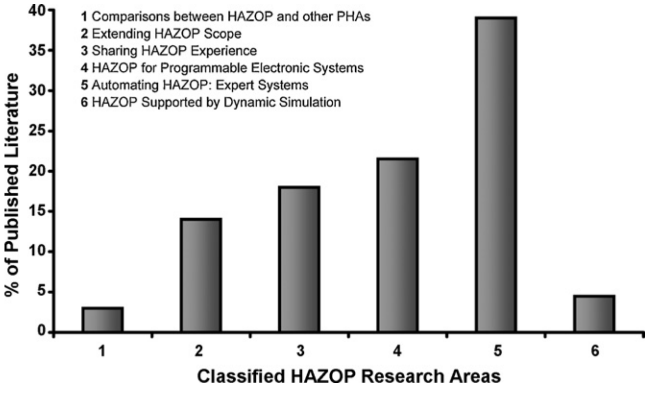

Fig. 2. HAZOP research lines proportion.

Table 3
Classification of literature according classified research areas.

Research topics	Papers considered	Percentage
1. Introduction to PHA	[1–7]	4.2
2. Introduction to HAZOP	[8–22]	9.1
3. HAZOP research areas		
3.1. Comparing HAZOP with other PHAs	[23–26]	2.4
3.2. Extending HAZOP scope		
3.2.1. Extending the hazard identification scope	[27–33]	4.2
3.2.2. Considering quantification	[34–40]	4.2
3.2.3. Considering human factors	[41–48]	4.8
3.2.4. Considering specific HAZOP modifications	[49–51]	1.8
3.3. Sharing HAZOP experience	[52–76]	15.2
3.4. HAZOP for programmable electronic systems		
3.4.1. Software safety assessment	[77–94]	10.9
3.4.2. Assigning a target safety integrity level	[95–107]	7.9
3.5. Automating HAZOP: expert systems	[108–160]	31.5
3.6. HAZOP supported by dynamic simulation	[161–166]	3.6

Over the 30 years since then, numerous other guidelines and books have appeared. Among the important contributions on adapting the technology for the processing industry are those of Knowlton [11], Nolan [12], Kletz [13–16], Lees [17], Wells [18], EPSC [19], Macdonald [20], and Casal et al. [21]. This plethora of publications illustrates the evolution of HAZOP as a vital technique applied worldwide that is recognized by legislation, and has demonstrated its effectiveness in identifying environmental, safety, and health-hazards. Knowlton [11] was the first author to develop a book focused only on HAZOP applications, giving valuable information on the creative process to generate deviations; Nolan [12] shared his practical experience discussing specific topics both for HAZOP and What If techniques. Both methodologies are fully described. The book also introduces tools for HAZOP time and costs estimation. The document was intended as a typical guideline and reference book to be applied at petroleum, petrochemical and chemical facilities by describing the nature, responsibilities, methods and documentation required in the performance of such reviews. Kletz [13–16], considered one of the most influential authors on several process-safety topics, wrote an excellent book defining in technical terms HAZOP and, at the same time, sharing his experience and thoughts with a characteristic entertaining personal style. Lees [17] and Wells [18] contributed their concepts of HAZOP development, and extended their focus to a wide-range of aspects of hazard identification and loss prevention. In 2000, EPSC [19] formulated new HAZOP guidelines adapting the methodology to the emergence of new technologies and sharing their considerable experience in using the technique most effectively. Finally, a British Standard [22], published in 2001, established and defined new requirements for carrying out a HAZOP, thereby clearly point-

Table 4
Essential HAZOP references.

Year	Author/Institution	Title	Paper	Guideline	Book	Standard
1974	Lawley	Operability Studies And Hazard Analysis	■			
1977	CIA	A Guide to Hazard and Operability Studies		■		
1981	Knowlton	Hazards and Operability Studies, The Guideword Approach			■	
1983	Kletz	“HAZOP & HAZAN”. Identifying and Assessing Process Industry Hazards (first edition)			■	
1986	Kletz	“HAZOP & HAZAN”. Identifying and Assessing Process Industry Hazards (second edition)			■	
1996	Lees	Loss Prevention in Process Industries Hazard Identification, Assessment and Control			■	
1991	HSE	Guidance on HAZOP Procedures for Computer-controlled Plants		■		
1992	Kletz	“HAZOP & HAZAN”. Identifying and Assessing Process Industry Hazards (third edition)			■	
1992	CCPS	Guidelines for Hazard Evaluation Procedures			■	
1994	Nolan	Application of HAZOP and What-if Safety Reviews to the Petroleum, Petrochemical and Chemical Industries			■	
1996	Wells	Hazard Identification and Risk Assessment			■	
1999	Kletz	“HAZOP & HAZAN”. Identifying and Assessing Process Industry Hazards (fourth edition)			■	
1999	Redmill	System Safety: HAZOP and Software HAZOP			■	
2000	EPSC	HAZOP: Guide to Best Practice. Guidelines to Best Practice for the Process and Chemical Industries			■	
2001	BS IEC 61882	Hazard and Operability studies (HAZOP Studies)—Application Guide				■
2004	McDonald	Practical HAZOPs, Trips and Alarms			■	

ing to its continuing importance as the most widely used technique in process plants and other types of facilities. Recently, Macdonald [20] updated the field in his book with the latest data on the characteristics of HAZOP, documenting how to carry out a HAZOP and connect it with future studies focused on Safety Integrity Level (SIL) assignments. The document concentrates on the application of hazard study methods and the actions that follow from them for providing protection against hazards. Additionally, the book provides training in three basic steps (i.e., identifying hazards, evaluating risks, and specifying risk reduction measures) that form part of the overall risk management framework for process facilities.

Additionally, we would like to mention that there exist internal corporative guidelines from process industries, although we cannot cite them due to confidentiality constraints. These guidelines present valuable information on how to perform HAZOP in processes that present equivalent or similar technology and intentions (e.g., petroleum refining units). Mostly, these guidelines establish criteria to conduct a standardized methodology when “hazoping” different processes from the same facility or corporation: the minimum expert team required for brainstorming, the size of nodes to be reviewed, team leader expectations, deviations to be analyzed are some of the factors taken into account.

Table 4 lists the most notable books and guidelines on HAZOP, highlighting the most essential and broadly used documentation needed for understanding its underlying concept and its evolution. Hereafter, we consider the papers that were published over the years, according to research area, and the evolution of process technology, and HAZOP methodology.

3. HAZOP research areas

3.1. Comparing HAZOP with other PHAs

This section illustrates research focusing on the analysis of HAZOP and compares it with similar safety-analysis systems. Generally, the emphasis in this section is on defining the intended coverage of a HAZOP study, and identifying other PHA techniques that complement its application.

After defining the starting point of a safety analysis and considering the differences between safety analysis and safety management, Suokas [23] evaluated the scope of four different methods: HAZOP; Action Error Analysis (AEA); Work Safety Analysis (WSA); and Management Oversight and Risk Tree (MORT). His aim was to identify and assess the coverage of the search procedures employed in these different methods for identifying accident contributors. He showed that research on the scope of HAZOP concentrated mainly on deviations in the physical subsystem, and in a lesser way, on those in the human subsystem, while lacking a description of a management subsystem. This shortcoming affected the value of HAZOP results. In a later paper, Suokas and Rouhiainen [24] reviewed the potential for quality evaluation, using results from several comparable investigations. They reaffirmed that HAZOP covered hazards induced by process deviations and human errors in manual operations, but organizational factors remained outside the methodology’s scope. They called for more research on management matters to incorporate them as a standardized element in safety and risk analyses, especially HAZOP.

Hoepffner [25] compared HAZOP’s features with two other PHA techniques, viz., Fault Tree Analysis (FTA),[1] and Failure Modes and Effects Analysis (FMEA).[2] The author defined HAZOP as being midway between them. HAZOP started according to the deductive approach (downward) postulating top events (deviations), and then followed the inductive method (upward) asking what would happen to the system. This definition revealed the reason for the success of HAZOP and underscored its widespread usage compared to other well-known analysis systems.

Montague [26] considered what single method or combinations of them should be used for process risk evaluations. He explored the values of three common ones: HAZOP, Facility Risk Review (FRR), and Quantitative Risk Analysis (QRA), illustrating their effectiveness in producing useful recommendations for improving safety. He concluded that selecting the right method is not a trivial task, and managers can make objective decisions only by seeing the types of results from various approaches.

3.2. Extending HAZOP scope

Some efforts were made to extend the scope of HAZOP. Its application in specific systems and the intention to analyze the particular features of these systems generated the need to consider possible combinations between HAZOP and other PHA techniques, or modifications. This field has accounted for the analyses of several systems and particularities, centering on human factors, new technologies such as Programmable Electronic Systems (PES), renewable energy systems, batch systems, and management factors. This section details this research work, excluding PES HAZOP

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[1] A deductive method, starting the investigation from a Top Event (TE) down to single source events.

[2] An inductive method wherein each element of the plant is analyzed to find failure modes, following the pathways upward to the top event.

that we discuss in a separate section because of its wide applicability. Additionally, there has been considerable work on applying the HAZOP to batch processes than is discussed herein; we will explore much of it when we discuss research on automating HAZOP and considering human factors.

3.2.1. *Extending hazard identification scope*

Comparing the structure and systematic execution of HAZOP and FMEA easily affirms that both techniques work similarly. While the hazard-identification stage in HAZOP is based upon using established guidewords and parameters for generating deviations of the design intent, FMEA considers the failure modes of specific equipment. This close relationship between HAZOP and FMEAs' definition features and their results generated much research on combining the two in studies to increase the efficiency and improve the quality of both reviews, focusing on their identification of hazards, operability problems, and reliability.

Post [27] suggested techniques for combining reliability studies and PHAs, based on HAZOP and FMEA techniques, by reviewing the development of these methodologies and suggesting how to integrate the two types of studies. Other authors discussed the same matter [28–30].

Trammel and Davis [31] combined the strengths of the HAZOP and FMEA methodologies to maximize their effectiveness, employing the hybrid PHA methodology to identify design weaknesses and to increase system uptime in semiconductor manufacturing process. Later, Trammel et al. [32] extended the utility of this hybrid method by adding Layer of Protection Analysis (LOPA) to evaluate and apply effective controls. They concluded that the HAZOP portion of this combination eased the selection of system limits and hazard identification, while the FMEA portion effectively estimated and evaluated risk. Incorporating LOPA to specifically evaluate and quantify existing or proposed Independent Protection Layers (IPLs) ensures the identification of the appropriate controls.

Burgazzi [33] determined the uncertainties of passive systems by comparing the findings from two hazard identification methods to assess the main sources of physical failures. FMEA analyzed the systems/components' reliability (well-engineered safety components), while HAZOP identified the reliability of physical phenomena (physical-phenomena stability). The author stated the need to include FMEA in analyses of passive components. While this technique enabled the identification of the most relevant uncertainty sources of the passive system's performance and generated a set of critical parameters, HAZOP helped in qualifying and eventually confirming the outcome of the earlier study.

3.2.2. *Considering quantification*

Many authors attempted to extend the HAZOP application from identifying hazards to evaluating their impacts. Bendixen and O'Neill [34] considered HAZOP and FTA as the best combination PHA techniques to do so. Their experience on conducting QRAs confirmed uncertainties in their execution. They concluded that a thorough HAZOP, linked carefully with the FTA, minimized the contributions of uncertainty from three areas of the QRA: (1) Which initiating events must be considered, (2) What is the frequency of occurrence of these initiating events, and (3) Which criterion was to be applied in consequence modeling estimation.

Ozog et al. [35,36] confirmed that this same combination was the most effective way to identify, quantify, and control risks. They believed that HAZOP is the most versatile technique for hazard identification in new and existing facilities, and that FTA is the most appropriate hazard-quantification technique.

Demichela et al. [37] developed the Recursive Operability Analysis (ROA), for the safety analysis of plants with multiple protection levels activated by the same process variable. They explored complex pathways by linking HAZOP results and FTA development, thereby effectively constructing accidental sequences that might lead to the top event (TE). The thermodynamic study used as the basis of ROA verified its successful application and showed which protection systems were effective against a given TE.

Recently, Cozzani et al. [38] developed a specific methodological approach to analyze comprehensively the risk from hazardous materials in marshalling yards. They considered the HAZOP analysis of railcar vessels, using a set of possible deviations of the process variables from the design values; thereafter, they evaluated the expected occurrence frequencies of the TEs by carrying out an FTA.

Shafaghi et al. [39] specifically considered the combination of checklists and HAZOP, applying this hybrid PHA technique to assess the hazards of an absorption heat pump. The objective of using a checklist is to identify major areas needing attention and/or further consideration; it is limited to certain questions and does not provide a mechanism for investigating problems. The authors showed that with a checklist for preliminarily recognizing hazards, HAZOP successfully identified many types of risks, sources of non-optimum system reliability, and also improvements in the heat pumps' design.

3.2.3. *Considering human factors*

In this section, we cite work on possible hazardous situations caused by human errors. These situations should be seen as human-process interaction (e.g., accidents that could be prevented by better training or instructions, better methods of operation, better design). Since standard HAZOP assessments focus only on the malfunction of equipment and process variables, methodologies were developed to consider human-machine interfaces, organizational style, management attitudes, procedures and training, and batch processes and pipeless plants. The importance of this work is reflected in the fact that between 50 and 90% of operational risk is attributable to human error [40].

Schurman and Fleger [41] proposed a novel method for incorporating analysis of hazards introduced by human error into standard HAZOP by adding a new set of guide words (such as missing, mistimed) and parameters (person, information, action) to focus on management and organizational factors that can contribute to risk. Their method employs conditional reliance on procedure/training as safeguard.

Baybutt's [40] new approach for delineating human-failures and human-factors issues that influence the hazardous scenarios revealed by PHA entails identifying types of human failures analogously to generating conventional HAZOP deviations. Human failures are identified by conceptually combining elements of three simple lists to prompt the PHA team in considering all the people involved with the process and their roles, the various functions they may perform, and the different types of errors they may make the combination (Person–Facility Aspect–Failure Type) producing the looked-for deviations (i.e., specific human failures).

Aspinall [42] also focused on addressing human factors in HAZOPs, and then restated the basic principles of HAZOPs in order to show how the established guide word-driven method could be used for human factors issues. The author illustrated how to proceed in any stage of a process lifetime and strongly strengthened the importance of a clear design intention (or activity intention) for defining additional deviations for human factors investigation.

Rasmussen and Whetton [43] suggested considering the process plant as a socio-technical system, linking hardware, software, operations, work organization, and other safety-related aspects. Their work described the first stage of a hazard identification process to identify critical areas and the need for further analyses.

Managerial vulnerabilities and organizational failures significantly contribute to causing accidents. Kennedy and Kirwan [44] discussed the requirement to develop a modified HAZOP for detecting specific safety-management vulnerabilities that could fail in practice; to carry out a HAZOP of safety-management systems required new, different information from that of traditional studies. Accordingly, they supported their proposal by functional task descriptions and decision-action diagrams, offering examples of this type of information, and defining the study's procedures, group selection, and the required guidewords. They validated their new approach by comparing the results obtained by MORT and FMEA. Further, they cited many references on safety-management systems issues. From a different point of view, but covering the same time-management requirements, Pátkai [45] considered the need for a data-management tool for aiding the HAZOP process. He justified the tools and methods he developed by generating more structured data, and collecting it for additional developments. Thus, safety experts could utilize the tool for HAZOP data-management and not only represent data intuitively, but search for important information from the analysis. Currently, there are available many commercial software packages developed specifically to ease the data management of a hazard-identification analysis. They are listed in [46].

Batch processes entail major human involvement, and its inherent technology must be treated differently from continuous processes. Automated batch processes allow some flexibility for change that must be considered in identifying hazards. Mushtaq and Chung [47] offered a formalized approach for applying HAZOP methodology to batch processes, suggesting examining a typical batch plant by dividing it into three operational phases; charge and discharge steps that are analyzed as a continuous process; and, reaction, reviewed by separating it into its different operations, such as mixing, and heating. They listed and interpreted new guide words for this discontinuous process, extending its application to the safe design of processes in pipeless plants. Justifying the methodology's time-consuming feature, the authors highlighted the need to have a computer-support tool to guide and document the study. We further discuss this work in session 3.5, automating HAZOP. An essential reference is Kletz's book [48], a valuable comprehensive assessment of human errors in chemical engineering. In this book, the author shares his expertise and views on human errors as a cause of accidents, and illustrates several accidents that have occurred, mainly in the oil and chemical industries (e.g., accidents due to a lack of physical or mental ability, accidents due to wrong decisions, accidents due to management errors).

3.2.4. Considering specific HAZOP modifications

Particular PHAs must consider different objectives, purposes, and scopes. Specific safety analyses might focus only on detecting major process hazards, such as fires, explosions and toxic releases. Baybutt [49] discussed the requirement for a specific PHA technique that directly and exclusively addressed major process accidents. HAZOP can be time-consuming as it aims to identify operability problems in many nodes. Major Hazard Analysis (MHA) begins by considering the first subsystem, and then moves directly to identifying the causes of scenarios originating in that node and resulting in the loss of containment; Baybutt gives a typical list of categories of initiating events. The results from this methodology can be linked with subsequent analyses, such as LOPA and QRA. Hence, the methodology is structural, matching "enabling events" and "scenarios", thereby affording a fuller description of the hazard scenario. Grossmann and Fromm [50] offered an alternative to undertaking full HAZOP studies by excluding irrelevant and trivial questions. They stated that in assessing an established process about 90% of the questions revealed no new information on the risk because it already was known, or the special combinations or process properties and malfunctions were not safety-relevant. Without sacrificing the principles of HAZOP, they overcame this disadvantage developing a special form of safety review, viz., "Mini-HAZOP". The main difference from a full-scope HAZOP was its restriction to meaningful combinations of guidewords.

Finally, focusing on HAZOP documentation, due to the amount of information and cause-consequence pairs highly related to abnormal situations in process facilities, Suzuki et al. [51] developed a HAZOP based operator decision support system (implemented by using Microsoft Access) with the aim to predict possible hazards. This tool could support operators to take corrective actions against abnormalities. The authors extended the HAZOP features by adding a database with valuable information to be used for maintenance personal and operators.

3.3. Sharing HAZOP experience

In this section we review much of the information in the open literature that is based on professional experience. Due to the inherent subjectivity in any PHA, it is important to share professional experiences about HAZOPs. Even though HAZOP is structured and systematic, it depends on human observation, judgment, and creativity. We do not intend that this review should be a destructive dissection, for a major benefit of hazard identification is its subjectivity [52] (its requirement for thought). Clearly, a most valuable way to learn and acquire expertise is sharing knowledge with others. Likewise, the extensive literature, described below, discusses experiences and applications based on executing HAZOP assessments.

Qureshi [53] explored the stages required to carry out a HAZOP, emphasizing the importance of the leader's experience and the team member's skills. Contrary to common belief, he concluded that HAZOP did not take any longer than reviews based on a checklist provided these considerations were taken into account. Many authors have defined parameters to improve the effectiveness of the HAZOP study. Thus, Mckelvey [54] suggested key elements that make HAZOP powerful and effective in identifying chemical-process hazards. He depicts eight basic steps explain its success, from defining the scope of the study to the following-up procedure ensuring that all recommendations from the study were addressed. In contrast, he uses six key problems to illustrate why HAZOP sometimes failed, the first of which was lack of experience. Mckelvey concluded that it was important to have the best possible input, the most experienced team, good communications, and enlightened, cooperative management to ensure success. Similarly, Jones [55] exposed HAZOP's benefits and pitfalls, concluding that the critical factor in success was the manner in which management responded to recommendations. In a rearrangement of Kletz's thoughts, Gujar [56] revealed some of the HAZOP lacunas. Several authors shared their experiences on HAZOP by defining stages of the study and considering particularities to improve them: the examples they gave included planning for HAZOP, HAZOP preparation, HAZOP team composition, hazard specialists' responsibilities, and timing [57–62]. Focusing on the documentation stage of a HAZOP study, Freeman [63] established a detailed HAZOP report content and detailed basic rules to developing one. Pully [64] described the manner in which HAZOP was performed for petroleum-refinery units, the types of results obtained, and the benefits from it. George [65] emphasized the process information required and its relevance to other PHAs, while Bullock et al. [66] exposed the unwitting abuse of HAZOP. Their article indicated that the quality of human input can be improved and abbreviated variants of the traditional HAZOP might be viewed with suspicion. Recently, Dunjó et al. [67] analyzed the evolution of HAZOP studies and highlighted the importance to develop a standardized methodology for selecting nodes in continuous chemical process facilities (e.g., oil and gas industry).

Over the years, HAZOP has been applied to a wide range of industries and activities, and to specific situations. Robinson [68] described how HAZOP was applied successfully and cost-effectively in existing operating plants, mechanical systems, electrical systems, computer systems, transports systems, and the like, highlighting the importance of developing a suitable model to represent these particular systems; several authors gave practical examples by applying HAZOP to a liquid-hydrogen filling station [69], steelworks [70], hydrogen plant [71], and large gasholders [72].

Kletz [73,74] validated the success of the HAZOP for incident investigation, explaining four accidents that might have been prevented. From the reverse point of view, Mahnken [75] described how case histories could help HAZOP, so demonstrating the connection between HAZOP guidewords and real-world accidents.

The strength and validation of HAZOP is well founded. Thus, from its first publication it has changed remarkably little, although it has been modified for specialized applications, such as batch processes, laboratory operations, mechanical operations, and even for identifying possible hazards in genetic engineering [76]. However, the industry was slow to recognize the need for incorporating additional HAZOP parameters for computer-controlled systems. Nevertheless, the several changes proposed for the HAZOP procedure would make it suitable for the PES. We cover this work in the next section.

3.3.1. HAZOP for Programmable Electronic Systems

The speed and flexibility of computers has fostered the increasing use of software in industry to control or manage safety-critical systems. Indeed, as systems become more and more complex, and faster and faster response time is required, the only feasible approach is to use a computer and software. However, while incorporating a computer to control, protect, and monitor the operation of a chemical plant has improved efficiency, at the same time it has introduced new routes to failure and potential risks. Because of the successful widespread use of HAZOP in the process industry, researchers and engineers are suggesting ways of adapting HAZOP (CHAZOP and PES HAZOP) to safety-critical systems [77]. This section describes the research aimed at adapting the traditional HAZOP to computer-controlled plants.

3.3.2. Software safety assessment

Andow [78] developed the first guideline on HAZOP procedures for computer-controlled plants, recommending using a framework similar to that of the conventional HAZOP. Kletz et al. [77] assembled wide-ranging information about the state-of-the-art of HAZOP studies undertaken in PES plants that focused on the current situation, identifying much research accomplished, although no agreed format for HAZOP was established. After describing four different CHAZOP schemes, the authors concluded that a total system view was required, and offered a systematic approach for developing a hazard identification methodology to assessed the system's safety, and improve its overall quality.

McDermid and Pumfrey [79] justified the HAZOP as the most appropriate study to assess all stages of the design and implementation life cycle because its inductive and deductive safety features support safety assessment. They propounded the essential principles of a software safety analysis based on applying a set of guidewords to suggest hypothetical failures. Lawrence and Gallagher [80] proposed undertaking software hazard analysis by focusing on the early stages of its life cycle. Subsequently, McDermid et al. [81] shared their experience using HAZOP in software systems, offering four examples using additional techniques, such as Software Hazard Analysis and Resolution in Design (SHARD), that they considered had useful, widespread applicability for investigating the safety properties of a range of computer-based systems. Earthy [82] highlighted the special benefit of HAZOP for software analysis in identifying the effects of interactions between software, its computer environment, and the real world in which it is used.

Nimmo [83] described the new skills needed to identify and correct new hazards introduced consequently to the growth in numbers of computer-controlled plants. He described how to add CHAZOP to the traditional HAZOP to improve the plant's safety integrity by dividing the entire analysis into two phases. The first phase encompasses the traditional HAZOP; the second looks specifically at the PES and its interactions with the process and operators. Collins [84] defined the new adaptations required for applying HAZOP to control systems, including the new information needed, its management, the required new skills of the leader and expert team, and modifications to the traditional HAZOP.

Redmill et al. [85] revealed common difficulties in preparing guidelines on applying HAZOP to PES, and gave suggestions on how to overcome them, listing them as actions and premises that must be accounted for. Two years later, they published a book elaborating on the technical – and managerial – requirements for executing HAZOPs on software systems [86].

After summarizing the research into software HAZOP, Fenelon and Hebbron [87] evolved some recommendations and drew together common threads of work. They proposed three different models of HAZOP: a formal model, an algorithmic one, and a causal one. The following year, they expounded upon the potential value of integrating these three models: HAZOP, Ward & Mellor, and Calculus of Communication Systems [88]. There was much more such work on modifying the traditional HAZOP; aspects treated included a new set of guidewords, management criteria, and new documentation [89–92].

Yang and Chung [93] formulated a novel modeling representation for identifying hazards related to computer-controlled processes. Called the Process Control Event Diagram (PCED), it expresses the control logic and its effects on the process, and complements P&IDs information and the combined features from Signed Directed Graph (SDG) and Event Time Diagram (ETD). Subsequently, Chung and Edwards [94] applied the same criteria to both batch and continuous computer-controlled plants.

3.4. Assigning a target safety integrity level

Because of the rapid evolution in automating the process industry, the industrial community has drawn up procedures to assess new requirements for assigning a target SIL for all Safety Integrity Systems (SIS) applications. Standards [95–97] describe them. The SIS consists of the instrumentation or controls installed for mitigating the hazard or bringing the process to a safe state in the event of a process upset. A SIS is used for any process in which the PHA has determined the insufficiency of the mechanical integrity of the process equipment, the process control, and other protective equipment to mitigate the potential hazard [98]. The features of a HAZOP study and the need to assign SIL for SIS revealed that the information obtained from HAZOP made it a serious candidate to use for linking its results with the input data required to start analyses for the SIL assignment; this situation now is being studied comprehensively. Particularly, the HAZOP final stage, during which the team identifies safeguards used to mitigate the hazardous events, affords valuable information for considering SIL assignments. Additionally, HAZOP has been combined with, and made consistent with Logic Trees (Fault and Event Trees), which are written and solved numerically in any complete risk analysis. When combined with Logic Trees, HAZOP becomes a powerful tool for plant design, allowing the designer to define the SIL in accordance with the appropriate event tree.

Summers [98] examined the six most common PHAs utilized throughout the process industries, highlighting the HAZOP study as the most interesting technique for functional safety requirements because it provided a prioritized basis for implementing risk-mitigation strategies. Five years later, she suggested that the features of LOPA offer a powerful, analytical tool for assessing the adequacy of protection layers to mitigate process risk [99]; again, HAZOP was deemed important in developing LOPA. The same point of view was considered in a study published in [100]. Dowell [101] followed the same direction, first describing the modified features of HAZOP for qualitatively assigning the required SIL, and the considering LOPA as a semi-quantitative technique for categorizing an event's severity, numerically estimating the initiating event's frequency, and obtaining numerical values of Probability of Failure on Demand (PFD) for each layer of protection. He concluded LOPA could be undertaken after HAZOP to calculate the needed SIL for most of SIS functions, and considering FTA for specific complex systems. Later, he illustrated specific criteria for generating scenarios automatically from HAZOP data to be employed in LOPA based on lesson-learned during HAZOP meetings and LOPA preparation [102].

Stavrianidis and Bhimavarapu [103,104] discussed the requirements established for the two functional safety standards discussed above. They outlined the steps required to assign target SIL considering the scope of HAZOP, from identifying process hazards to developing accident scenarios for every initiating event. Thereafter, depending on the specific system, the application of several semi-quantitative or quantitative techniques will finalize the SIL procedure. Finally, detailed information about LOPA features and application is contained in [105–107], references that introduce the LOPA as a technique to be used between HAZOP (as a qualitative hazard identification technique) and Fault Tree Analysis (as a quantitative tool). Likewise, LOPA starts from the HAZOP results and semi-quantitatively accounts for the risk reduction of each safeguard by comparing risk values from the corporation's criteria for unacceptable risk. Moreover, if further detailed analysis is required, FTA can be applied.

3.5. *Automating HAZOP: expert systems*

The development of expert systems for automating HAZOP undoubtedly was the most wide-ranging research related on HAZOP topics. HAZOP can be a difficult, time-consuming and labor-intensive activity, and many researchers have attempted to develop expert systems to resolve these drawbacks. In this section, we discuss the global efforts made towards this goal, arranging the studies under specific topics and authors. In discussing the authors, we take the papers chronologically. We especially note a 1996 review of the older work on PHA automation [108].

Parmar and Lees [109,110] were among the first authors attempting HAZOP automation. They described a method of modeling fault propagation for hazard identification implemented in a computer-based interactive facility. They used a rule-based approach to automate HAZOP, and demonstrated its application identifying hazards in the same water separator system used by Lawley [9]. One year later, Heino et al. [111] established a rule-based expert system called HAZOPEX, an advanced development environment consisting of a Lisp workstation (Symbolics) and a hybrid expert system shell (KEE). In addition to Common Lisp, Flavors and Windows, its numerous extensions offered the possibility of using object hierarchies, rules, truth maintenance, world-based alternative exploration, predicative calculus language, and interactive graphics equipped with picture – and image – libraries. Other expert-system prototypes based on classical knowledge bases are proposed in [112–115]. The prototype developed in [112] was based on a PC version of Prolog, language considered excellent for expressing logic and performing symbol manipulation. A basic inference engine was enhanced and tailored. The authors showed the potential use of HAZOP expert system in both an educational and industrial environments. Wang et al. [113] developed a knowledge-based simulation architecture as a tool able to allow a HAZOP expert to build and modify simulation models at a simulation-language independent level and without the constant presence of a simulation software expert. Its application was focused on large-scale process plant modeling. Another knowledge-based system, embodied in HAZID [114] was developed, tool which included the screening process designs at an early stage, the initial evaluation of proposed process modifications and the analysis of human team performance. The main feature of HAZID was the no possibility for interaction at run-time, excluding user control over the generation of cause-consequence links. Heeyeop et al. [115] developed a system open-ended and modular in structure to make it easy to implement wide process knowledge for future expansion. The tool had a frame-based knowledge structure for equipment failures and process properties, as well as rule networks for consequences reasoning which used both forward and backward chaining. Readers interested on further information related to expert systems based on classical knowledge bases should address to [116–119].

One important factor to consider in managing HAZOP studies is the time required to execute the entire analysis. Freeman et al. [120] made the first attempt to plan HAZOP studies with an expert system, setting up a way to estimate how long and how many work-hours a HAZOP study takes. They based their estimate on the number of major equipment items to be analyzed, the system's complexity, and the experience of the HAZOP team leader. Five years later, Khan and Abbasi [121] improved this model, adding new factors and variables. The proposed model takes into account four different parameters (preparation time, meeting time, delay and report writing); and uses multivariable empirical equations. Additionally, the preparation and study time are function of three parameters: number of P&IDs, complexity of P&IDs and the skills of the team leader.

Chung [122] developed a qualitative analysis of the behavior of a process plant. The system, termed Qualitative Effects Engine (QUEEN), takes the topology of a plant as input and generates the complete SDG from a library of models describing individual units in the plants. Additionally, Chung introduced the first steps from the Artificial Intelligence research community focusing upon automating the qualitative hazard-identification procedure. Later, Jefferson et al. [123] used QUEEN as an engine to emulate various forms of hazard identification, particularly describing its employment as the basis of an automated hazard-identification tool, emulating conventional HAZOP studies.

Kang et al. [124] formulated developed the Automatic Hazard Analyzer (AHA) using the expert system shell G2 composed of three knowledge bases, viz., a unit, an organization, and a material. The first modeled a process unit in different terms of variable and function, the organizational knowledge base gave information about spatial arrangement of process units and streams, and finally, the material–knowledge base considered the material's properties according to the National Fire Protection Association's (NFPA's) code. The system also had three hazard-analysis algorithms: the deviation analysis, the malfunction analysis, and the accident analysis. This paper was the origin of future research by the same authors [125], work that described and applied the model to olefin dimerization plants. The results showed that more possible accidents could be identified and that the development methodology had the ability to capture process hazards in terms of both functional failure and unexpected variable deviations, thereby improving the quality of the hazard analysis.

Galluzzo et al. [126] described their methodology for HAZOP automation on continuous systems; it included both cause – and consequence – models. The former contained the data needed to propagate the deviations of variables from the unit backwards to the previous one to find the causes of deviations, including operative faults and failures. Nevertheless, several differences precluded the method's applicability to batch or semi-continuous systems due to its time-depending nature. For a batch plant, the procedural phases must be considered as nodes, in addition to the equipment unit. Accordingly, the authors developed software support, based on their previous work, by adding models to accommodate phases of the operational procedure and the equipment units [127,128]. Furthermore, Cocchiara et al. [129] integrated a method for analyzing single interlock systems, starting from the output of the plant's HAZOP analysis.

Venkatasubramanian and his colleagues published numerous papers within the framework of automating HAZOP. First, Venkatasubramanian and Vaidhyanathan [130] developed a knowledge-based system, called HAZOPExpert that was implemented using an object-oriented architecture Gensym's G2 expert system shell. HAZOPExpert had some disadvantages in representing the process-generic HAZOP models of the process units. Likewise, Vaidhyanathan and Venkatasubramanian [131] devised an approach to address these difficulties, introducing a representation called HAZOP-Digraph Model (HDG), defining a digraph as a representation tool that offers the infrastructure for graphically representing the causal models of chemical process systems so that they will be transparent to the user. Further, the basic HAZOPExpert generated many more consequences compared to those identified by the expert team. Accordingly, the authors proposed a semi-quantitative reasoning methodology to filter and rank those consequences [132]. For batch procedures, Srinivasan and Venkatasubramanian [133] integrated Petri nets – mathematical languages used for modeling discrete event systems – and subtask digraphs to account for the operational procedures required in batch processes; their system was called Batch HAZOPExpert. Other researchers worked to improve particular features both for continuous – and batch – processes, and for management requirements [134–142]. Srinivasan et al. [134,135] integrated knowledge-based and mathematical programming approaches for process safety verification; approach capable to perform exact analysis when required and thus overcomes qualitative ambiguity. Srinivasan and Venkatasubramanian [136,137] automated HAZOP analysis of batch chemical plants. Firstly, the authors presented the knowledge representation framework by combining high-level Petri nets and digraphs with object-oriented knowledge representation for the development of a flexible and user-friendly system called Batch HAZOPExpert (implemented in G2). Finally, the authors described the system features and its performance on an industrial case study. The same authors [138] expanded the scope of PHA automation, not only for hazard identification, but also covering the entire PHA process. They proposed an integrated framework and a knowledge-based system, called PHAzer. The system uses qualitative digraph based models of unit operations to identify hazards, dynamic mathematical models to perform detailed safety evaluation, and digraph and fault tree models to synthesize and analyze fault trees. Further detailed information can be found in [108,139,143], references that afford a perspective on intelligent system for PHA.

Khan and Abbasi also published much work on automating HAZOP. Their first paper [144] analyzed the conventional HAZOP, identifying several factors affecting its effectiveness and reliability; they concluded that its conventional structure must be modified to ensure fast, efficient, and reliable results. They described their approach for optimizing HAZOP studies (OptHAZOP) that rests upon expert system knowledge. This base comprised a large collection of facts, rules, and information on various components of process plants, such as process deviations, their causes, and their immediate consequences for various components. To improve their first version, they generated a new knowledge-based software tool, termed TOPHAZOP to speed up the OptHAZOP [145]. It identified general and specific causes and consequences of all probable process-deviations. The whole expert system (the so-called EXPERTOP) consisted of the following main modules: Knowledge-base, inference engine, and user interface [146]. Further work to improve specific features of this system and other applications are reported in [147–149]. Khan and Abbasi [147] reviewed the available techniques and methodologies for carrying out risk analysis in chemical process industries. Additionally, the paper presents a set of methodologies to conduct risks analysis. The same authors present a risk analysis methodology, called ORA (Optimal Risk Analysis) based on a set of tools and techniques developed previously for themselves [148]. Finally, Khan [149] proposed a knowledge-based expert system for automating HAZOPs for offshore process facilities. The framework was aimed to enable HAZOPs at significantly lesser costs and with better accuracy than conventional HAZOPs. The framework associated an extensive and dynamic knowledge-base with the software which incorporated details of all typical process units and works out numerous modes of failure for given input operational conditions.

Similarly, the STOPHAZ project represents the major efforts made in Europe. The development of this project, financed by the European Commission, took important steps towards applying knowledge-based systems to safety analysis of chemical plants [150]. The focus of the STOPHAZ project was to provide a software tool able to reduce the overall time taken to complete the safety study on a developed process design. Other work includes the development of a Qualitative Hazard Identifier (QHI) [151], a system that uses a set of qualitative equations derived from a quantitative description of the plant behavior. The set of equations was steady-state-simulated such that conclusions could be drawn from the resulting qualitative values of process quantities. The HAZOPTool [152] considered only one deviation in a single process unit at one time and offered its user the possibility to evaluate the generated candidate event chains after each step of this kind. Thus, the user had a major influence on which deviations and process units were studied more thoroughly and which of the considered event chains would be stored as part of the final HAZOP report. Finally, a knowledge-base computer program called COMHAZOP [153] was developed as an aid for hazard and operability studies in process plant. Graf and Schmidt-Traub [154,155] introduced a new model-based approach for identifying hazards creating qualitative equipment models, and implementing them with the statechart language–state-transition diagrams facilitating the modeling of hierarchy and modularity, extremely helpful for chemical plants.

Recently, Bragatto et al. [156] integrated Product Lifecycle Management (PLM) systems to support HAZOP analyses throughout the lifecycle of a process plant with a prototype software tool called IRIS. The tool usefully enriches and adapts the knowledge gained by analysis, and integrates the different documents managed by PLM systems. Additionally, PLM systems aimed at an overall management of the plant's digital models, such as drawings, diagrams and 3D models, which represent the plant from different points of view, offer capabilities of automating the design process and linking the data produced during the various phases of project development. LÜ and Xiong [157] applied Signed Directed Graphs to computer-aided HAZOP studies together with fault diagnosis that automatically finds all possible abnormal causes or adverse consequences. However, some problems remain, such as eliminating redundant consistent paths, and overcoming inherent qualitative ambiguities by combining SDG with quantitative information. Other recent work is described in references [158–160]. Guimarães and Franklin [158] developed a methodology which uses risk priority number for scale any parameter characteristics of the system and a fuzzy inference system for estimating risk from expert opinion about the quantification of the linguistic variables, named FuzzyHAZOP_rpn. Finally, in [159], Trucco and Leva developed a simulator for approaching human errors in complex operational frameworks (e.g., plant commissioning). The authors integrated the quantification capabilities of human reliability assessment (HRA) methods with a cognitive evaluation of the operator. The Probabilistic Cognitive Simulator (PROCOS) directly evaluated how a corrective action influenced the probability of success or failure of a critical activity. Recently, Hangzhou et al. [160] applied a SDG-based HAZOP. They illustrated the methodology and applied it in a case study on polyvinyl chloride plant. The results of their analysis demonstrate the effectiveness of the method.

3.6. HAZOP supported by dynamic simulation

Currently, ongoing work is applying process simulation in safety-related studies. Combining process-simulation features with hazard-identification techniques delivers invaluable results for safety examinations. This methodology's purpose is to determine risk from operational disturbances, and to develop means for effective risk reductions [161]. Svandova et al. [162] recently suggested complementing HAZOP studies with simulations.

Eizenberg et al. [163] introduced HAZOP into process-safety education, both for educational purposes and training operators. Combining HAZOP with dynamic simulation could offer students the means for exploring the consequences of emergencies. They might try various strategies for dealing with the event, and rapidly assess the effectiveness of their postulated responses in preventing a component failure, culminating in a serious accident. Further, in quantifying HAZOP by dynamic simulation, the possible process deviations can be examined and threshold values identified that might lead to potential hazard scenarios. Thus, Ramzan et al. [161] introduced a systematic methodology, supported by dynamic simulation and conventional HAZOP, for finding operational failures and analyzing the effects of design improvements in a safety system. Whereas conventional HAZOP covers both safety and operational failures, dynamic simulations guide safety teams towards generating optimization proposals for systems. The application of this methodology was illustrated in a separate paper [164].

Labovský et al. [165,166] integrated a mathematical-model approach with HAZOP analysis. They initially applied the methodology of a chemical reactor, highlighting the combination as a useful tool for equipment in all steps of its design, not only during its operational stage. The mathematical-model revealed deviations from normal operating conditions, and analyzed device's response. Later, the methodology was applied in a MTBE production unit to illustrate the importance of both steady-state analysis and the deviations dynamical response. This approach could serve directly for examining the safety of industrial equipment, or might function as a robust basis for a subsequent conventional HAZOP study.

4. Conclusions

The present paper is the first HAZOP review to gather all the related literature with the purpose of classifying the main research areas and review the state-of-the-art of the HAZOP methodology. We focused the review on studies carried out in chemical-process facilities, reviewing about 165 papers, covering a period from 1974, the year when the first formal HAZOP paper published, to the present. Over these 35 years, many authors have focused upon improving specific HAZOP aspects, but most papers were published in the last 15 years. The first and only HAZOP Standard was published in 2001. We hope that our review and categorization of the publications will facilitate further access to information for those researching and practicing HAZOP. We classified the literature we reviewed into six main areas (Sections 3.1–3.6), considering specific aspects for improving HAZOP and organized these areas chronologically to allow us to follow the evolution of HAZOP research. We found that early authors focused primarily on detecting the features of HAZOP (e.g., the contributions that could be analyzed). Later, authors conducted research aiming to extend theses features, and as process facilities were evolving, they turned to exploring new deviations and control options. Independently, efforts began on automating HAZOP by developing expert systems; this is the most wide-ranging area of HAZOP research. Recently, authors have been displayed interest in merging HAZOP features with dynamic simulation, mainly for teaching purposes.

Analyzing the areas of HAZOP research, we found that 80% of the total publications are related to three main areas: (1) sharing HAZOP experience (18%), (2) HAZOP for Programmable Electronic Systems (22%), and (3) expert systems for automating HAZOPs (40%). Sharing professional expertise (e.g., providing valuable information on how to treat specific situations, new applications and approaches), is considered to be a key feature in training team leaders, HAZOP managers, and team members. On the other hand, HAZOP for Programmable Electronic Systems (e.g., research focused on adapting HAZOP features for reviewing new technologies) is considered fundamental to keeping HAZOP up-to-date.

Based on the reviewed documents, we found HAZOP to be the foundation of process safety – and risk – management programs. It is the most studied PHA method; indeed, abundant research has centered on readapting HAZOP as process systems evolved. However, the first and only HAZOP Standard needs to be enhanced (e.g., it does not include guidance on how to break a process into nodes). It is noted that valuable advances have been made by developing expert systems for HAZOP automation. These findings do much to illuminate specific processes, their aspects and particularities, but most HAZOPs in the process industry still are being conducted by human expert teams. Considering the HAZOP state-of-the-art and our experience on conducting hazard identification analyses, we identified that more research is needed in addressing the following issues:

(a) HAZOPs conducted by human beings are subject to the analyst's bias, experience, knowledge, and creativity. One should attempt to gain knowledge from the experience of parties involved, but also it could be valuable to standardize the HAZOP structure for processes that present equivalent technology.
(b) A related human factor issue appears when hazard identification is focused not only on analyzing typical process deviations but also initiating events leaded by human errors. These events normally present higher frequencies of occurrence than others (e.g., a control failure). While endeavors have been focused on improving the expert team motivation for finding these types of causes, their integration in the HAZOP structure still remains incomplete.
(c) Identifying causes and hazardous scenarios from PES. Our experience confirms improvements could be done when looking for potential causes of control device failures. When linking the HAZOP results to other techniques intended to gather Safety Integrity Level values of Safety Integrity Systems to be implemented, the list of initiating events that could lead the hazardous scenario may not be complete (e.g., why the Level Control Valve is not closing when analyzing more level?) This deviation could be caused from an error in the sensor, due to either the logic solver or the actuator (for many causes). Including a detailed failure mode for PES, would easier facilitate the subsequent analysis for SIL needs for risk reduction.
(d) Most endeavors for standardizing HAZOP studies have been done with the aim to automate its execution. Expert Systems development is the most powerful tendency in the evolution of HAZOP, and disciplines such as process engineering and artificial intelligence have been merged. Knowledge bases, Petri nets, signed digraphs and other principles contributed to better

understand process industries with focus on improving hazard identification. A considerable amount of work has been conducted in this challenging field; yet more research and application/verification of expert systems is needed to effectively apply them in hazard identification and loss prevention control.

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Glossary

AEA: Action Error Analysis
AHA: Automatic Hazard Analyzer
AIChE: American Institute of Chemical Engineers
ANSI: American National Standards Institute
CCPS: Center for Chemical Process Safety
CIA: Chemical Industries Association
CHAZOP: Control or (Computer) Hazard and Operability analysis
COMHAZOP: Computer program as an aid for HAZOP studies
DOE: US Department of Energy
ETD: Event Time Diagram
EPSC: European Process Safety Center
ETA: Event Tree Analysis
FMEA: Failure Modes Effects Analysis
FRR: Facility Risk Review
FTA: Fault Tree Analysis
HAZAN: hazard analysis
HAZOP: hazard and operability study
HAZROP: Hazard, Reliability, and Operability Analysis
HDG: HAZOP-Digraph Model
HRA: Human Reliability Analysis
HSE: Health and Safety Executive
ICI: Imperial Chemical Industries
IEC: International Electrotechnical Commission
IHAS: Integrated Hazard Analysis System
IPL: Independent Protection Layers
ISA: International Standards Association
LOPA: Layer Of Protection Analysis
MHA: Major Hazard Analysis
MORT: Management Oversight and Risk Tree
NFPA: National Fire Protection Association
ORA: Optimal Risk Analysis
OSHA: Occupational Safety and Health Administration
PCED: Process Control Event Diagram
PES: Programmable Electronic Systems
PFD: Probability of Failure on Demand
PFDs: Process Flow Diagrams
PHA: Process Hazard Analysis
P&IDs: Piping & Instrumentation Diagrams
PLM: Product Lifecycle Management
PROCOS: Probabilistic Cognitive Simulator
PSM: Process Safety Management
QHI: Qualitative Hazard Identifier
QRA: Quantitative Risk Analysis
QUEEN: Qualitative Effects Engine

RCM: Reliability Centered Maintenance
ROA: Recursive Operability Analysis
SDG: Signed Directed Digraph
SHARD: Software Hazard Analysis and Resolution in Design
SIL: Safety Integrity Level
SIS: Safety Integrity System
STOPHAZ: Support Tool for Process Hazard Analysis
WSA: Work Safety Analysis