Heliyon 9 (2023) e13550

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

# A systematic review of consequence modeling studies of the process accidents in Iran from 2006 to 2022

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A R T I C L E I N F O

*Keywords:*
Consequence modeling
Process accidents
PHAST
ALOHA
Systematic review

A B S T R A C T

Analytical models and the prediction of accidents and their consequences are important tools for preventing accidents in the industry. Therefore, the present study was conducted to review process accident consequence modeling in Iran (2006–2022), helping improve incident modeling, and creating a context for preventing these accidents. In this study, the articles of 5 international Embase Medline/PubMed databases, ProQuest, Scopus, Google Scholar, and Web of Science, and four Iranian databases SID, MagIran, IranMedex, and IranDoc were examined using the PRISMA checklist. After reviewing the studies, 40 articles were included in the final analysis. The results showed that 25 studies used PHAST software, 11 studies used ALOHA software and 4 studies used ALOHA and PHAST software together. The highest number of studies was conducted in Imam Khomeini Port and Asaluyeh city, respectively. In addition, the number of studies published in Persian was more than in other studies. There was no similar agreement between the results of the two software in providing correct results at low concentrations. PHAST software also provided more accurate results than ALOHA over longer distances in stable and relatively stable weather conditions. The study and identification of hazards and scenarios in the studies that used PHAST software were more, more accurate and more coherent than in the studies that used ALOHA software. It is suggested that in future studies the same scenario can be compared with PHAST, ALOHA, and newer modeling software such as Fire Dynamics Simulator (FDS).

## 1. Introduction

Today, having a safe environment and industry is essential for the general public, professionals, and industrialists. In addition, the proximity of industrial units to population centers has increased the economic and social effects of accidents. The best industrial units in developed countries are not safe from accidents despite enforcing safety rules and developing methods for identifying and assessing hazards [1]. Hence, occupational accidents are considered the third leading cause of death in the world [2].

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https://doi.org/10.1016/j.heliyon.2023.e13550
Received 19 September 2022; Received in revised form 28 January 2023; Accepted 2 February 2023
Available online 7 February 2023
2405-8440/

In recent decades, the frequency and severity of accidents in process industries have increased significantly because the speed of industrialization and also the population density in the vicinity of industrial complexes are increasing rapidly [3].

These industries often have dangerous chemicals and different units are in variable temperature and pressure conditions. Therefore, the possibility of accidents such as toxic leakage, explosion and fire is very high [4]. Accidents in these units are not only a threat to the equipment and people working inside the unit but may also lead to domino effects [5]. According to the Department of Safety, Supervision, and Management of Hazardous Chemicals in China, from 2016 to 2018, 620 chemical accidents occurred and resulted in the death of 728 people [6]. In the study by Zhao et al., the results showed that there were 3974 hazardous chemical accidents in China (2006–2017), resulting in 5203 deaths [7].

The development of technologies and their complexity in different process industries has changed the philosophy of safety from the post-occurrence approach to the pre-occurrence approach. This approach is based on the identification and prevention of risk before an accident occurs so that the reduction of accidents in the chemical industry shows the positive effects of this process. As a result, today' the safety of these industries has received more and more attention. Therefore, extensive work has been done to identify the consequences of accidents in the process industries [4]. Predicting the probability of accidents and evaluating their possible consequences form the basis of all accident prevention and mitigation strategies [8].

Predicting different processes is done by two main methods of experimental studies (laboratory method) and theoretical studies (mathematical modeling). Laboratory methods are less considered because of the problems they have in preparing conditions that are completely similar to the real conditions [9]. One of the important tools related to accident prevention in the industry is analytical models and prediction of accidents and their consequences, which have been explained to understand the effects, influential, and contributing factors in the occurrence of occupational accidents and have been developed in various studies [10]. Modeling the effects and consequences of accidents is possible using analytical methods, theoretical formulas, and commercial software [9].

There are many modeling software such as Process Hazard Analysis Software Tool (PHAST), DEGADIS, SLAB, HGSYSTEM, and, Areal Locations of Hazardous Atmospheres (ALOHA), which are used depending on the type of study [11,12]. Recently, Computational fluid dynamics (CFD) is also used to calculate the magnitude or severity of the consequence. Depending on the purpose of the study, the complex features of CFD models, such as considering geometries and complex three-dimensional environments, etc., have turned them into valuable software in this field [13,14].

In recent years in Iran, process industries and their subsequent accidents have grown significantly. The increasing importance of this issue and also the growth of various approaches and software for modeling the consequence of accidents, including ALOHA and PHAST have led to various studies in this field. ALOHA software is used for various applications in chemical crisis management, access, storage, information management, assessing compliance of activities with environmental regulations related to maintenance and Chemicals, etc. [15–17]. Despite some limitations, its use can provide good results. Modeling the outcome of material leakage with this software has been done in various studies. Hui and Gunning (2012) investigated the modeling of spill consequences from natural fuel power plants with this software [18]. Singh et al. (2012) modeled the consequences of chlorine, phosgene, and epichlorohydrin spills with ALOHA and used it to prevent future accidents and integrate it into risk assessment [19]. In the study of Lee et al., the modeling of the consequences of ammonia gas release and the preparation of an emergency response plan was also studied [20].

PHAST process risk analysis software is also one of the most famous software available in this field. This software can model different stages of release of materials (including pure or mixed materials) in the environment, including discharge, modeling materials lighter and heavier than air, evaporation from a liquid pool and finally spreading materials. In this software, both continuous and sudden releases can be modeled and atmospheric conditions are also considered as one of the input data [21,22].

International review studies, despite their advantages, cannot represent the trend of modeling studies in a particular country, and this issue can differ in countries. We believe that reviewing studies in one country can provide useful information in the field of prevention and control of consequences, which may not be possible in other countries due to the different characteristics of processes and industries.

Therefore, considering the importance of extensive process and industrial accidents and their prevention, and the controversial accident consequence modeling studies in Iran, the present study pursues the following basic objectives.

a. Providing a context to prevent accidents
b. Help improve incident modeling
c. Choosing the appropriate software for modeling, and
d. The study of modeling the consequences of process accidents in Iran from 2006 to 2022.

## 2. Method

The present study was conducted by reviewing the texts and reports related to the modeling of the consequence of chemical process accidents in Iran. The reporting method of the present study was based on the PRISMA checklist.

### 2.1. Search strategy

For this purpose, published sources from March 21, 2006, to the end of 2021 were searched and related articles were reviewed. Five international bases/Embase Medline/PubMed, ProQuest, Scopus, Google Scholar, and Web of Science, and four Iranian bases SID, MagIran, IranMedex, and IranDoc have been investigated. In this study, the Snowball Method was used [23]. In this way, the sources of the articles were used to find other supplementary sources, provided that the relevant article is in the time frame of the study. The selected keywords for international databases were five categories including: 1- Modeling (Modeling and Consequence modeling), 2- Accident and consequence (Accident and consequence), 3- Process industries (Chemical industries, Chemical, Chemical process, and Chemical industry process), 4- software (PHAST and ALOHA) and 5- Iran. The equivalent of the same keywords in Persian was also searched in Iranian databases.

### 2.2. Inclusion and exclusion criteria

#### 2.2.1. Release time or period

Articles published in peer-reviewed journals from 2006 to the end of 2021 were included in this study.

#### 2.2.2. Article type

In this study, all related research articles (original articles) were reviewed. Conference papers were also excluded from this study. Articles that used modeling methods to assess the consequence of accidents were reviewed if they had a full text and the results of the study were mentioned, and articles that did not have a full text were deleted.

#### 2.2.3. Research question

The objectives of each related article had one of the following criteria:

A. Expresses consequence modeling or incident modeling in process industries
B. Consequence modeling with PHAST or ALOHA software

#### 2.2.4. Language

The articles Published in English and Persian were selected to review.

#### 2.2.5. Quality assessment and screening

The initial search for studies was done by one person. Screening of studies, extraction of results, and also evaluation of quality control of articles were performed separately by two people (A and B). If there was no agreement between the two people, team leader (A) would comment on the article.

For better results, the two authors independently evaluated the applicability of articles related to inclusion criteria. At the end of the search, the abstracts were carefully reviewed and the full text of the related articles was reviewed using the PRISMA checklist.

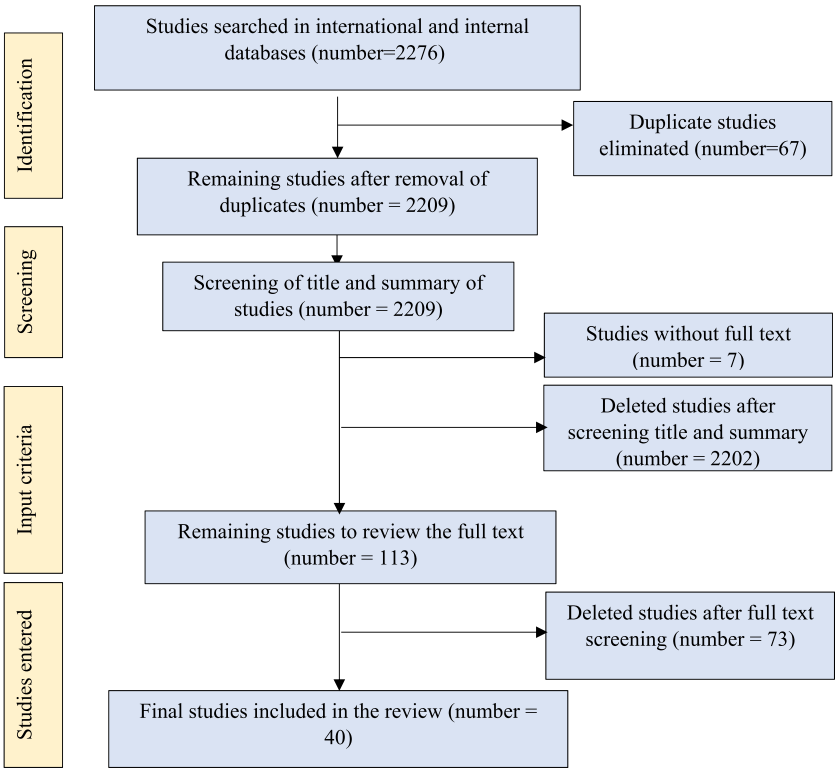


**Fig. 1.** Literature search flow diagram.

### 2.2.6. Extraction of data

After the final identification of the studies, the characteristics of each study were summarized as follows: name of the authors, year of publication, country of the first author, and type of study.

## 3. Results

A total of 2276 search results were returned and screened for eligibility (Fig. 1). 113 articles entered the next stage of review after removing duplicate articles by checking the titles and abstracts. Then the full text of the articles was reviewed and 40 articles were

**Table 1**
Summary of studies.

| No. | First Author | Year | Industry/unit | City of study | Modeling software | type of study | Language of publication | Reference No. study |
|---|---|---|---|---|---|---|---|---|
| 1 | Rashtchian | 2007 | Ammonia tanks In Petrochemical | Khorasan | PHAST | – | Persian | [24] |
| 2 | Jabari Gharabagh | 2009 | Petrochemical | Mahshahr | ALOHA | Case study | English | [25] |
| 3 | Zarei | 2011 | Hydrogen production unit | Tehran | PHAST | Cross section | English | [26] |
| 4 | Zarei | 2012 | Hydrogen production unit | – | PHAST | Case study | Persian | [27] |
| 5 | Ghashghaei | 2013 | Container Terminal | Bandar Imam Khomeini | PHAST ، ALOHA | – | Persian | [28] |
| 6 | Ghashghaei | 2013 | Container Terminal | Bandar Imam Khomeini | PHAST | – | Persian | [29] |
| 7 | Jafari | 2013 | Hydrogen production unit | – | PHAST | Case study | Persian | [4] |
| 8 | Beheshti | 2014 | Petrochemical | – | ALOHA | – | Persian | [30] |
| 9 | Parvini | 2014 | CNG refueling station. | Azad Shahr | PHAST | Case study | English | [31] |
| 10 | Golbabaei | 2015 | Oil platform | Persian Gulf region | PHAST | Case study | Persian | [32] |
| 11 | Mohammadfam | 2015 | Oil refinery | – | PHAST | – | English | [33] |
| 12 | Haghnazarloo | 2015 | Paint factory | – | PHAST | Analytical | English | [34] |
| 13 | Fatemi | 2015 | Chlorine storage | Shahr-e– -Rey | ALOHA | – | English | [23] |
| 14 | Kamaei | 2015 | Refinery | Asaluyeh | PHAST | – | Persian | [35] |
| 15 | Jafari | 2016 | Sarcheshmeh Copper Complex | Kerman | PHAST | Cross section | Persian | [36] |
| 16 | Shahedi Aliabadi | 2016 | Gas refinery | – | PHAST | Cross section | Persian | [37] |
| 17 | Kamaei | 2016 | Spherical LPG tank in a refinery | – | PHAST | Cross section | Persian | [9] |
| 18 | Pouyakian | 2016 | Petrochemical | Kermanshah | PHAST | – | English | [38] |
| 19 | Ghorbani | 2017 | Chemical Material Career Tankers | | PHAST ، ALOHA | Practical | Persian | [39] |
| 20 | Atabi | 2017 | Tehran-Qazvin Highway | Tehran-Qazvin | PHAST ، ALOHA | – | Persian | [40] |
| 21 | Shirali | 2017 | Petrochemical | Asaluyeh | ALOHA | – | Persian | [41] |
| 22 | Moradi Hanifi | 2017 | Gas power plant | – | ALOHA | – | Persian | [42] |
| 23 | Sadeghi Yarandi | 2018 | Compressed natural gas station | – | PHAST | Case study | Persian | [43] |
| 24 | Shirali | 2018 | CNG Fuel Stations | Ahvaz | ALOHA | Case study | Persian | [44] |
| 25 | Harati | 2018 | Petrochemical | – | PHAST | – | Persian | [45] |
| 26 | Cheraghi | 2018 | Petrochemical | – | PHAST | – | Persian | [46] |
| 27 | Pourbabaki | 2018 | Oil refinery | – | ALOHA | – | Persian | [47] |
| 28 | Sharifi | 2018 | Gas Refinery | Ilam | PHAST | – | Persian | [48] |
| 29 | Khorram | 2018 | Nuclear power plant | Bushehr | PHAST | – | Persian | [49] |
| 30 | Rastimehr | 2018 | CNG Fuel Stations | Isfahan | ALOHA | – | Persian | [50] |
| 31 | Movahed | 2019 | Gas Refinery | – | PHAST | – | Persian | [51] |
| 32 | Mohammadi | 2019 | Steel Company | – | ALOHA | Practical | Persian | [52] |
| 33 | Sadeghi Yarandi | 2019 | Industrial slaughterhouse | Qom | PHAST | – | English | [53] |
| 34 | Sabeti | 2019 | Oil terminal | – | PHAST | – | Persian | [54] |
| 35 | Khorram | 2019 | Nuclear power plant neighborhood | Bushehr | PHAST ، ALOHA | – | Persian | [55] |
| 36 | Panahi | 2019 | Gas refinery | – | ALOHA | – | Persian | [56] |
| 37 | Abbaslou | 2019 | Petrochemical | Asaluyeh | ALOHA | – | English | [57] |
| 38 | Nabhani | 2019 | Petrochemical | Bandar Imam Khomeini | PHAST | case study | English | [58] |
| 39 | Sadeghi Yarandi | 2020 | Industrial refrigerators | Qom | PHAST | – | Persian | [59] |
| 40 | Bahmani | 2020 | Petrochemical | Bandar Imam Khomeini | PHAST | – | Persian | [60] |

included in the final analysis. The screening process of the search is shown in Fig. 1.

### 3.1. Description of selected studies

The characteristics of the studies entered are given in Table 1. Of these, 10 studies were published in English and 30 studies in Persian. Fig. 2 shows the number of studies conducted in each city, as well as 16 studies that did not list the city of study.

The software used in modeling for 25 PHAST studies was 11 ALOHA studies and 4 studies of ALOHA and PHAST software. All studies reviewed were published in reputable scientific research journals. The type of studies studied was 8 case studies, 4 cross-sectional studies, 2 applied studies, 1 analytical study, and 25 studies that did not mention their type of study.

Of these studies, 10 studies in the petrochemical industry, 8 studies in the oil and gas refinery, 3 studies in the CNG station, 3 studies in the hydrogen plant, 2 studies in the nuclear power plant, 2 studies in terminals and container ports, 2 studies in the platform and Oil terminal, 2 studies in the country's road transport fleet, 1 study in industrial slaughterhouse ammonia tanks, 1 study in industrial cold storage ammonia tanks, 1 study in power plant, 1 study in the compressed natural gas station, 1 study in factory Dyes, 1 study in chlorine storage, 1 study in Sarcheshmeh copper complex and 1study in the steel industry.

### 3.2. Results of studies based on ALOHA software

The first step; before consequence modeling, is the identification of reservoir hazards and potential scenarios in the industry. Then the modeling of scenarios and consequences was done according to the identified risks. In most of the studies that used the ALOHA method, the desired scenario was extracted according to the opinions of industry experts. Also, in the case of studies, the number of scenarios has been limited. However, risk assessment methods specific to process industries such as HAZOP were also used to identify accident scenarios in these studies.

The parameters studied in the studies that used ALOHA include: 1- parameters related to the source of emission (source and time of emission), 2- atmospheric parameters (such as ambient temperature, humidity, wind direction and velocity, type of land) and 3 - Parameters related to the chemical (such as volume and amount of storage, flash point, boiling point, etc.)

In addition, the results and output of ALOHA software are based on three criteria: Acute Exposure Guideline Levels (AEGLs) and PAC for Toxic Vapor and to prepare an emergency response program from the Emergency Response Program Guideline (ERPG). These three criteria classify high-risk areas in terms of pollutant leakage and fire into three levels. Leakage of various chemicals was one of the common results the studies that used the ALOHA method. Their results were different in seasons and types of materials according to Table 2.

### 3.3. Results of studies based on PHAST software

The results showed that in the studies that used PHAST software, identification and analysis of scenarios were better, more accurate, and more coherent than the studies that used ALOHA software. Risk assessment methods in studies that used PHAST software; most were HAZOP, Bowtie, FTA, ETA, and HAZID, and incident analysis methods such as Tripod BETA. The scenarios and phenomena studied in the studies were very different and due to differences in circumstances, their results are difficult to integrate. However, the predominant phenomena (consequences) in the studies were pool fire, jet fire, flash fire, BLEVE phenomenon, and explosion. The results of some studies are available in Tables 3 and 4. Also, due to the differences in the studied scenarios, it is not possible to average or aggregate the obtained numbers.

## 4. Discussion

There is different software for modeling accidents and their consequences, which are available for a fee as well as free. PHAST and

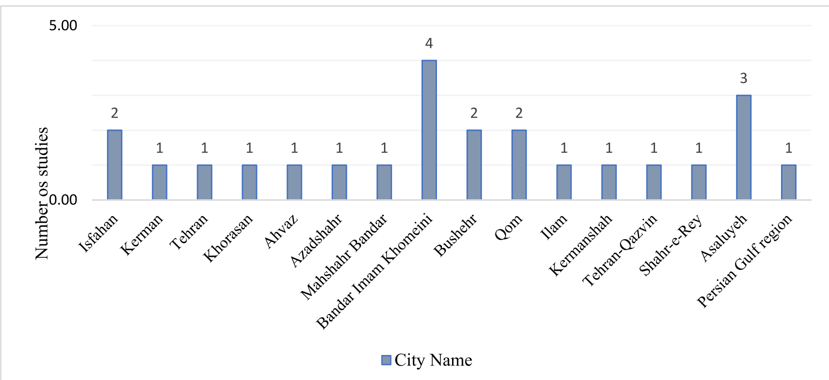


**Fig. 2.** Number of studies conducted in different cities of the country.

**Table 2**
Results of chemical leakage by ALOHA method in terms of AEGL & PAC.

| No. | Type of Substance | Lethal concentration (ppm) | | Safe distance based on AELG (km) | | | Reference No. |
|---|---|---|---|---|---|---|---|
| 1 | Chlorine | Minimum | 68 | AELG 1 | 0.65 | | [25] |
| | | Average | 242 | AELG 2 | 0.35 | | |
| | | Maximum | 859 | AELG 3 | 0.185 | | |
| 2 | Chlorine | Minimum | 0.5 | AELG 1 | 8.3 | | [23] |
| | | Average | 20 | AELG 2 | 4.8 | | |
| | | Maximum | 30000 | AELG 3 | 1.9 | | |
| 3 | Hexane | Minimum | 1200 | AELG 1 | 0.526 | | [30] |
| | | Average | – | AELG 2 | – | | |
| | | Maximum | 7200 | AELG 3 | 0.160 | | |
| 4 | Methane | Minimum | 65000 | AELG 1 | 0.073 | | [44] |
| | | Average | 230000 | AELG 2 | – | | |
| | | Maximum | 400000 | AELG 3 | – | | |
| 5 | Carbon disulfide | Minimum | 13 | AELG 1 | 1.9 | | [47] |
| | | Average | 160 | AELG 2 | 0.9 | | |
| | | Maximum | 480 | AELG 3 | 0.6 | | |
| 6 | Natural Gas (leaking diaphragm 80 mm) | Minimum | 4400 | AELG 1 | 0.106 | | [42] |
| | | Average | – | AELG 2 | – | | |
| | | Maximum | 26400 | AELG 3 | 043.0 | | |
| | Natural gas (leaking diaphragm 130 mm) | Minimum | 4400 | AELG 1 | 0.0198 | | [42] |
| | | Average | – | AELG 2 | – | | |
| | | Maximum | 26400 | AELG 3 | 0.081 | | |
| | Natural gas (leaking diaphragm 300 mm) | Minimum | 4400 | AELG 1 | 0.579 | | [42] |
| | | Average | – | AELG 2 | – | | |
| | | Maximum | 26400 | AELG 3 | 0.235 | | |
| 7 | Methane (Creating a 3 cm hole in the tank and form a flammable vapor cloud) | Minimum | 5000 | AELG 1 | 0.266 | | [50] |
| | | Average | 30000 | AELG 2 | 0.116 | | |
| | | Maximum | 50000 | AELG 3 | 0.089 | | |
| 8 | Methane (Creating a 20 cm gap in the tank and form a flammable steam cloud) | Minimum | 5000 | AELG 1 | 0.340 | | [50] |
| | | Average | 30000 | AELG 2 | 0.138 | | |
| | | Maximum | 50000 | AELG 3 | 0.107 | | |
| 9 | Ammonia | Minimum | 30 | AELG 1 | 7.8 | | [57] |
| | | Average | 160 | AELG 2 | 3.3 | | |
| | | Maximum | 1100 | AELG 3 | 1 | | |
| 10 | Methane | Minimum | 65000 | PAC-1 | Summer: 0.154<br>Winter: 0.212 | | [56] |
| | | Average | 230000 | PAC-2 | Summer:0.062<br>Winter: 0.068 | | |
| | | Maximum | 400000 | PAC-3 | Summer:0.039<br>Winter: 0.036 | | |
| 11 | Ammonia | Minimum | 15000 | AELG 1 | 1.7 | | [41] |
| | | Average | – | AELG 2 | – | | |
| | | Maximum | 90000 | AELG 3 | 0.5 | | |
| 12 | Benzene | | | | Summer | Winter | [52] |
| | Leakage 5 mm | Minimum | 52 | – | 0.019 | 0.022 | |
| | | Average | 800 | – | <0.01 | <0.01 | |
| | | Maximum | 4000 | – | <0.01 | <0.01 | |
| | Leakage 25 mm | Minimum | 52 | – | 0.091 | 0.101 | |
| | | Average | 800 | – | 0.013 | 0.013 | |
| | | Maximum | 4000 | – | <0.01 | <0.01 | |
| | Leakage 100 mm | Minimum | 52 | – | 0.883 | 0.757 | |
| | | Average | 800 | – | 0.169 | 0.115 | |
| | | Maximum | 4000 | – | 0.059 | 0.030 | |

ALOHA can be considered representative of the most common outcome evaluation software. Each software uses previously established empirical or analytical models to estimate the extent and distance of property damage or loss of life that may occur as a result of an accident.

ALOHA is an independent software program developed by the US Environmental Protection Agency and the National Oceanic and Atmospheric Administration in 1982. The primary purpose of this software is to simulate the airborne releases of hazardous chemicals [8].

PHAST also includes models designed for hazard analysis of scenarios such as discharge and dispersion, jet fires, pool fires, fireballs, and toxic hazards of a release including indoor toxic dose calculations. This software uses a geographic information system (GIS) to display the results of the results on maps and plans [8].

Therefore, the present research deals with the objectives of investigating the consequences of process accidents in Iran (2006–2022), creating a basis for preventing accidents, improving accident modeling, and choosing the right software for modeling process industries with ALOHA or PHAST. One of the important results of this study is to examine the challenges of this software in

**Table 3**
Summary of the results of some of the dominant phenomena (consequences) calculated with PHAST software.

| NO | Scenario type | Seasonal conditions | Radiation rate (KW/M$^2$) | Destruction radius (meters) | | | Explosion intensity (bar) | Reference No. |
|---|---|---|---|---|---|---|---|---|
| 1 | Jet fire | Regardless of the season | 4 | 275 | | | – | [33] |
| | | | 12.5 | 210 | | | | |
| | | | 37.5 | 165 | | | | |
| 2 | Vapor cloud explosion | Regardless of the season | – | 280 | | | 0.01 | [33] |
| | | | | 110 | | | 0.17 | |
| | | | | 70 | | | 0.83 | |
| 3 | BLEVE | Regardless of the season | – | 5.4 | | | 1 | [31] |
| | | | | 3.4 | | | 4 | |
| | | | | 2.2 | | | 9 | |
| 4 | Pool fire | Regardless of the season | 4 | Sudden release: 140 | | | – | [35] |
| | | | | Leakage from the reservoir: 60 | | | | |
| 5 | Jet fire | Regardless of the season[1] | | 1.5F | 5D | 1.5D | | [43] |
| | 25 mm | | 4 | 95.82 | 89.65 | 86.23 | | |
| | 50 mm | | 4 | 100.09 | 100.28 | 99.56 | | |
| | 150 mm | | 4 | 122.51 | 135.13 | 128.96 | | |
| | 25 mm | | 12.5 | 66.58 | 63.96 | 59.36 | | |
| | 50 mm | | 12.5 | 92.45 | 90.55 | 86.64 | | |
| | 150 mm | | 12.5 | 112.33 | 119.38 | 115.66 | | |
| | 25 mm | | 37.5 | 44.69 | 40.63 | 42.85 | | |
| | 50 mm | | 37.5 | 76.85 | 79.33 | 77.89 | | |
| | 150 mm | | 37.5 | 109.82 | 105.45 | 111.28 | | |
| 6 | Jet fire | Warm seasons | – | 85–105 | | | – | [32] |
| | | Cold seasons | – | 80–100 | | | – | |
| 7 | Flash fire | Warm seasons | – | 110 | | | – | [32] |
| | | Cold seasons | – | 115 | | | – | |
| 8 | Pool fire | Warm seasons | 4 | 37 | | | – | [32] |
| | | | 12.5 | 25 | | | | |
| | | | 37.5 | 14 | | | | |
| | | Cold seasons | 4 | 38 | | | | |
| | | | 12.5 | 24 | | | | |
| | | | 37.5 | 13 | | | | |
| 9 | Flash fire | Regardless of the season | 4 | 481 | | | – | [37] |
| | | | 12.5 | 328 | | | | |
| | | | 37.5 | 248 | | | | |
| 10 | Jet fire | Regardless of the season | – | 330–360 | | | – | [37] |
| 11 | Jet fire | Regardless of the season | 4 | 165 | | | – | [24] |
| | | | 12.5 | 130 | | | | |
| | | | 37.5 | 110 | | | | |
| 12 | Pool fire | Regardless of the season | 4 | 180 | | | – | [24] |
| | | | 12.5 | 117 | | | | |
| | | | 37.5 | 100 | | | | |
| 13 | Flash fire | Regardless of the season | – | 48 | | | – | [34] |
| 14 | Jet fire | Regardless of the season | 4 | 110 | | | | [34] |
| | | | 12.5 | 40 | | | | |
| | | | 20 | <40 | | | | |
| 15 | Jet fire | Regardless of the season | 370 | 250 | | | – | [27] |
| 16 | Flash fire | Regardless of the season | – | Day: 140 | | | – | [27] |
| | | | | Night: 131 | | | | |
| 17 | Vapor cloud explosion | Regardless of the season | – | Day:55 | | | – | [26] |
| | | | | Night:60 | | | | |
| 18 | Jet fire | Regardless of the Season | 37.5 | 65 | | | – | |
| | | | 12.5 | 80 | | | | |
| | | | 4 | 105 | | | | |
| 19 | Pool fire | Regardless of the Season | 37.5 | 105 | | | – | [51] |
| | | | 12.5 | 170 | | | | |
| | | | 4 | 275 | | | | |
| 20 | Flash fire | Regardless of the Season | 37.5 | 80 | | | – | [51] |
| | | | 12.5 | 60 | | | | |
| 21 | Jet fire Leakage of a 5 mm, 25 mm and 100 mm | Regardless of the season | 5 mm: 2.4 | – | | | – | [45] |
| | | | 25 mm: 9 | | | | | |
| | | | 100 mm:14 | | | | | |
| 22 | Flash fire Leakage of a 5 mm, 25 mm | Regardless of the season | | – | | | – | [45] |

(continued on next page)

**Table 3** (*continued*)

| NO | Scenario type | Seasonal conditions | Radiation rate (KW/M$^2$) | Destruction radius (meters) | | | | Explosion intensity (bar) | Reference No. |
|---|---|---|---|---|---|---|---|---|---|
| | and 100 mm | | 5 mm: 0.15<br>25 mm: 1.1<br>100 mm: 39 | | | | | | |
| 23 | BLEVE | Regardless of the season | – | 105 by 100 m<br>165 by 168 m | | | | 1.103 0.2768 | [9] |
| 24 | Explosion | Warm seasons | – | 204 | | | | – | [46] |
| | | Cold seasons | | 256 | | | | – | |
| 25 | Complete tank rupture | Summer[2] | – | 1[3] | | | | – | [59] |
| | | | | 570.20 | | | | | |
| | | Winter | | 349.09 | | | | | |
| 26 | Sudden release of gas from spherical tanks | Regardless of the season | – | 513 | | | | – | [48] |
| | Leakage of condensate in cylindrical tanks | | | 180 | | | | | |
| | LPG leak on loading | | | 506 | | | | | |
| | Feller shutdown | | | 228 | | | | | |
| 27 | Jet fire 1-butane | Spring | 190.4 | 10 | 50 | 150 | Full | | [38] |
| | Leakage of a 10 mm, 50 mm | | | 200.9 | 318.63 | 400 | 173 | – | |
| | and 150 mm hole and Full | Summer | 190.4 | 191.9 | 304 | 400 | | – | |
| | rupture | Fall | 190.4 | 198.81 | 315.15 | 400 | 173 | – | |
| | | Winter | 190.4 | 190.4 | 302.2 | 400 | 173 | – | |
| 28 | Flash fire 1-butane | Spring | 40 | 10 | 50 | 150 | Full | – | [38] |
| | Leakage of a 10 mm, 50 mm | | | 26.9 | 105 | 304 | 2530 | | |
| | and 150 mm hole and Full | Summer | 40 | 33.15 | 119 | 347 | 1938 | – | |
| | rupture | Fall | 40 | 10 | 106 | 303 | 2386 | – | |
| | | Winter | 40 | 92.14 | 114 | 328 | 1771 | – | |
| 29 | Complete ammonia leakage from the tank | The first 6 months of the year | – | 1[4] | 2 | 3 | | – | [53] |
| | | | | 920.37 | 699.58 | 203.481 | | | |
| | | The second 6 months of the year | | 569.38 | 384.86 | 748.38 | | | |
| | Jet fire (leakage from the tank) –Oil | | | | | | | | |
| | Leakage 25 mm | Regardless of the season | 320 | 7.2 | | | | – | |
| | Leakage 50 mm | | 400 | 14 | | | | 19 | |
| 30 | Leakage 100 mm | | 400 | 22 | | | | 19 | [54] |
| 31 | Pool fire (leak from the tank) – oil | Regardless of the season | | | | | | | [54] |
| | Leakage:25 mm | | 77 | 46 | | | | – | |
| | Leakage:50 mm | | – | – | | | | – | |
| | Leakage:100 mm | | 23 | 109 | | | | – | |
| 32 | Explosion consequence (tank leak) | Regardless of the season | | | | | | | [54] |
| | Leakage 25 mm | | – | The explosion does not occur | | | | – | |
| | Leakage 50 mm | | – | 19.8 | | | | 19.7 | |
| | Leakage 100 mm | | – | 60.3 | | | | 19.7 | |
| 33 | Flash fire (tank leak) | Regardless of the season | | | | | | | [54] |
| | Leakage 25 mm | | – | 5.8 | | | | – | |
| | Leakage 50 mm | | – | 29.96 | | | | – | |
| | Leakage 100 mm | | – | 64.8 | | | | – | |
| 34 | Jet fire (leakage of connections) | Regardless of the season | | | | | | | [54] |
| | Inlet | | 380 | – | | | | – | |
| | Outlet | | 300 | – | | | | – | |
| 35 | Pool fire (leakage of connections) | Regardless of the season | | | | | | | [54] |
| | Inlet | | 76.7 | – | | | | – | |
| | Outlet | | 41 | – | | | | – | |
| 36 | Flash fire (leakage of connections) | Regardless of the season | | | | | | | |
| | Inlet | | – | 30.9 | | | | – | |
| | Outlet | | – | 5.7 | | | | – | |
| 37 | Rapid release of chlorine | Regardless of the season | | | | | | | |
| | Reach a concentration of 20 ppm | | – | During the day: 1040<br>At night: 1459 | | | | – | [49] |
| | Reach a concentration of 3 ppm | | – | During the day: 2811<br>At night: 5212 | | | | – | |

(*continued on next page*)

**Table 3** (*continued*)

| NO | Scenario type | Seasonal conditions | Radiation rate (KW/M$^2$) | Destruction radius (meters) | | Explosion intensity (bar) | Reference No. |
|---|---|---|---|---|---|---|---|
| 38 | Methanol pool fire | Regardless of the season | 10 | 130 | | – | [29] |
| 39 | Gas leak | Regardless of the season | 4 | 60 | | – | |
| | Sudden gas discharge | | 4 | 140 | | – | |
| 40 | Jet fire | | | Day | Night | | [60] |
| | Leakage 10 mm | Summer | 12.5 | 4.29 | 4.37 | – | |
| | | Winter | 12.5 | 4.51 | 4.49 | | |
| 41 | Jet fire | Summer | 12.5 | 25.25 | | 25.40 | [60] |
| | Leakage 50 mm | Summer | 37.5 | 20.40 | | 20.74 | |
| | Summer | Winter | 12.5 | 25.93 | | 25.87 | |
| | | Winter | 37.5 | 20.35 | | 21.65 | |
| 42 | Jet fire | Summer | 12.5 | 69.35 | | 69.93 | [60] |
| | Leakage 150 mm | Summer | 37.5 | 57.26 | | 57.5 | |
| | | Winter | 12.5 | 71.32 | | 70.3 | |
| | | Winter | 37.5 | 59.4 | | 59.1 | |
| 43 | Leakage from the loading line | Regardless of the season | 300 | 232 | | | [58] |
| | Leakage from the tank manhole (outlet line) | | 372 | 507 | | | |
| | Rupture in the spherical butane tank | | 4 | 1100 | | | |
| 44 | Small leak<br>Medium Leakage<br>large leak | Warm weather of the day<br>Cold weather of the night | Complete rupture of the reformer: 1970 | Complete rupture of the desulfurization reactor:<br>225 m in day and 200 m in nigh; Sudden fire:<br>140 m in day and 132 m in night | | | [4] |

[1] In this study, it was assumed that the air velocity was 1.5 and 5 m/s and the air flow was neutral or stable.(1.5F, 5D and 1.5D).

[2] In this study, summer is the representative of the average weather conditions of the first 6 months of the year and winter is the representative of the average weather conditions of the second 6 months of the year.

[3] The process conditions of the two ammonia reservoirs of the studied industrial slaughterhouse are as follows: Reservoir 1: Temperature = $-$ 8 °$C$, Pressure = 2.5 bar, Fluid volume = 1.1 $m^3$. Reservoir 1: Temperature = $-$ 12 °$C$, Pressure = 2 bar, Fluid volume = 3.82 $m^3$.

[4] The process conditions of the three ammonia reservoirs of the studied industrial slaughterhouse are as follows: Reservoir 1: Temperature = $-$ 12.5 °$C$, Pressure = 249.99 kPa, Fluid volume = 4.155 $m^3$. Reservoir 2: Temperature = $-$ 15 °$C$, Pressure = 226.99 kPa, Fluid volume = 1.884 $m^3$. Reservoir 3: Temperature = $-$ 34 °$C$, Pressure = 97.99 kPa, Fluid volume = 1.570 $m^3$.

process industries according to modeling conditions.

### 4.1. *Identifying scenarios for modeling*

After searching for the necessary articles and screenings, 40 related studies were finally included in the final analysis. The first step in the studies was to identify the scenario for modeling. The results of the present study showed that to identify the scenarios, several methods have been used which can be divided into two categories: qualitative (expert opinion, review of texts, and opinion of industry experts) and quantitative (risk assessment methods Tripod BETA, HAZOP, Bowtie, FTA, ETA, and HAZID).

Therefore, several scenarios were examined and due to the case nature of most scenarios, it was not possible to integrate all of them and present a final result. Also, considering that fire, explosion, and release of toxic substances are three types of frequent and severe accidents in the process industry [61] choosing the appropriate method to identify hazards is very important. Since HAZOP and HAZID methods have been developed specifically for process industries [62] it seems that the choice of these two methods to identify possible scenarios in the event of an accident is more appropriate.

### 4.2. *Features of PHAST and ALOHA software and related challenges*

A review of various modeling studies in Iran showed that ALOHA and PHAST software was the most used in modeling studies, which has been proven in other studies [62]. These two software predict and model the consequence of a possible accident by considering factors such as emission source, weather conditions, and chemical structure as well as the type of scenario under study [33]. Of course, there were differences in modeling, results, and outputs obtained from these two software, which can be selected according to the purpose of the study. ALOHA software is simpler than PHAST and only outputs based on the three criteria of AEGLs, PAC, and ERPG, and its images show the range of vulnerabilities based on these three criteria [63]. PHAST software, in addition to examining these two criteria and with the help of SAFETY software, also identifies individual and collective risks of accidents. Of course, there are other differences between the two software, including the identification of chemical evaporation from the pond, chemical evaporation from the spring, ground surface spring, and the momentum effect of the spring in PHAST software, which in

**Table 4**
Summary the results of some of the dominant phenomena (consequences).

| ROW | The results of PHAST | | | The results of ALOHA | | | Related study |
|---|---|---|---|---|---|---|---|
| 1 | Type of pollutant | Concentration limit | Hazard distance (Meter) | Concentration limit | Hazard distance (Meter) | | [39] |
| | Chlorine | LC1(PPM):122 | 620 | LC1(PPM):122 | 932 | | |
| | Ammonia | LC1(PPM):10647 | 129 | LC1(PPM):10647 | 980 | | |
| | Benzene | LC1(PPM):12817 | 23 | LC1(PPM):12817 | No value specified | | |
| | Toluene | LC1(PPM): 4262 | 22 | LC1(PPM): 4262 | No value specified | | |
| 2 | Chlorine | ERPG 1(ppm): 1 | 20027 | ERPG 1(ppm): 1 | 7000 | | [40] |
| | | ERPG2(ppm): 3 | 10983 | ERPG2(ppm): 3 | 4400 | | |
| | | ERPG3(ppm): 20 | 3004 | ERPG3(ppm): 20 | 2000 | | |
| | Ammonia | ERPG 1(ppm): 25 | 28792 | ERPG 1(ppm): 25 | 10000 | | |
| | | ERPG2(ppm): 150 | 9067 | ERPG2(ppm): 150 | 5100 | | |
| | | ERPG3(ppm): 750 | 1793 | ERPG3(ppm): 750 | 2800 | | |
| | Benzene | ERPG 1(ppm): 50 | 2971 | ERPG 1(ppm): 50 | 1800 | | |
| | | ERPG2(ppm): 150 | 1105 | ERPG2(ppm): 150 | 913 | | |
| | | ERPG3(ppm): 1000 | 135 | ERPG3(ppm): 1000 | 292 | | |
| | Toluene | ERPG 1(ppm): 50 | 1046 | ERPG 1(ppm): 50 | 1100 | | |
| | | ERPG2(ppm): 300 | 302 | ERPG2(ppm): 300 | 331 | | |
| | | ERPG3(ppm): 1000 | 92 | ERPG3(ppm): 1000 | 137 | | |
| | 1.3 butadiene | ERPG 1(ppm): 10 | 28528 | ERPG 1(ppm): 10 | 8000 | | |
| | | ERPG2(ppm): 200 | 2150 | ERPG2(ppm): 200 | 2700 | | |
| | | ERPG3(ppm): 2000 | 308 | ERPG3(ppm): 2000 | 919 | | |
| 3 | Hydrogen cyanide (AC) | ERPG 1(ppm): – | – | ERPG 1(ppm): – | – | | [55] |
| | | ERPG2(ppm): 10 | 50000 | ERPG2(ppm): 10 | | | |
| | | ERPG3(ppm): 25 | 3267 | ERPG3(ppm): 25 | | | |
| | Cyanogen chloride (CK) | ERPG 1(ppm): – | – | ERPG 1(ppm): – | – | | |
| | | ERPG2(ppm): 0.05 | | ERPG2(ppm): 0.05 | 10000 | | |
| | | ERPG3(ppm): 4 | | ERPG3(ppm): 4 | 7800 | | |
| | Cyanogen bromide (CB) | ERPG 1(ppm): – | – | ERPG 1(ppm): – | – | | |
| | | ERPG2(ppm): – | | ERPG2(ppm): – | | | |
| | | ERPG3(ppm): – | | ERPG3(ppm): | | | |
| 4 | Styrene | 61000 PPM | 10.5 | AEGL-3: 1100 ppm | Warm Season: 38 | Cold Season: 38 | [28] |
| | | 11000 PPM | 10.8 | AEGL-2: 130 ppm | 114 | 67 | |
| | | 5500 PPM | 18.8 | AEGL-1: 20 ppm | 631 | 329 | |

ALOHA software they cannot be calculated. A study conducted by the victim and his colleagues showed that the risk distances provided by different software are sometimes very different from each other [39]. For example, in this study, according to LC1, the most dangerous chemical by ALOHA software is ammonia with a hazard distance of 980 m and according to PHAST software, chlorine with a hazard distance of 620 m. In a study conducted by Atabi et al. at high concentrations (based on ERPG-3), ALOHA and PHAST software provided relatively close results, while at low concentrations (based on ERPG-1), low-risk distances accounted for a large dispersion ratio. In other words, the software could not provide the correct results at low concentrations and there was no uniform agreement between the results of the two software [40]. The study conducted by Khorram et al. showed that in stable and relatively stable atmospheric conditions at high concentrations (ERPG-3) PHAST software provided relatively close results. ALOHA software has also provided completely identical results in lower concentrations (ERPG-2) with similar atmospheric conditions. Therefore, comparing the results based on the criteria for emergency response planning showed that PHAST software in more stable and relatively stable weather conditions has more accurate results than ALOHA over long distances. According to the Khorram study, the accuracy and power of PHAST software in modeling low concentrations are higher than ALOHA [55]. Also, in the study conducted by Ghashghaei et al., it was found that the release of styrene chemical was less according to the toxic Levels of Concern (LOCs) defined in ALOHA software and the distance from the danger range to the source of danger was longer than PHAST software, which can indicate high sensitivity. This can indicate the high sensitivity of ALOHA to the release and toxicity of substances for the environment and humans [64]. Therefore, by examining the results of different studies, it can be said that the analysis of a scenario with two different software may produce different values and results. This difference in the results can be the result of different calculations and formulas used in the software [65].

Therefore, ALOHA allows modeling for BLEVE (boiling liquid expanding vapor explosion), VCE (vapor cloud explosion), jet fire, and pool fire. ALOHA has an extensive chemical library that can be extended by the user. The software uses weather data that can be entered by the user or directly from a weather station. It has an easy-to-use graphical interface and display and includes a mapping program called MARPLOT that enables customized overlays to show area features and vulnerable populations [8]. ALOHA results can be unreliable in conditions of very low wind speeds, very stable atmospheric conditions, wind shifts, terrain steering effects, and concentration roughness. According to the results, it can be said that ALOHA does not consider the effects related to fire or chemical reactions, particles, solutions/mixtures, and buildings. PHAST considers emissions from leaks, pipe ruptures, relief devices, vessel ruptures, and ventilation. Providing quick and accurate results and comprehensive reports and graphs for easy display of results are other advantages of PHAST [8].

### 4.3. Literature review of international consequence modeling

Table 5, examines the consequence modeling studies with different software, their goals, and results. As it was shown in the present study, each of the software has specific uses and weak and strong points.

**Table 5**
International Consequence modeling studies.

| Row | Title or objectives | Software | Results (Application, advantages or disadvantages) |
|---|---|---|---|
| 1 | Comparison of six widely-used dense gas dispersion models [66,67] | ALOHA, PHAST, HGSYSTEM, SLAB, SCIPUFF, and TRACE | -Uncertainties responsible for model error include discharge models, the effect of liquid rainout and pool formation, the atmospheric dispersion models, the effect of terrain and chemical reactions (including photolysis), dry deposition, and the toxic effects models.<br>-All models consistently overpredicted the number of casualties in the incidents. |
| 2 | Verification and validation of outcome models [68] | PHAST | -Being more comprehensive<br>-Properly showing the effect of momentum, two-phase leakage, evaporation from the pond, etc. |
| 3 | release of ammonia and hydrogen fluoride in America [68] | PHAST, SLAB, DEGADIS, and ALOHA models | The results showed that the PHAST model has the lowest relative error. |
| 4 | The general performance of the 17 models in this comparison with JR II field observations of chlorine clouds [69]. | Implementation of a comparative study of 17 dense gas dispersion models such as ALOHA, PHAST by scientists in seven countries | These models can satisfactorily simulate the observed maximum arc and their variation with wind distance at this flat desert site. |
| 4 | Modeling of time-varying dispersion for releases including potential rainout [70] | PHAST | It accounts for dense and buoyant gases, 2-phase releases, droplet modeling, and rainout.<br>For rain cases, an integrated pool diffusion and evaporation model is included.<br>In its most recent versions, it includes improvements for modeling along short-duration wind propagation and time-varying propagation. |
| 5 | -Presentation of modeling advances by the two groups involved: the UK Health and Safety Executive (HSE) and the US National Center for Atmospheric Research (NCAR)<br>-Predictions from DRIFT, PHAST, CFD, and the NCAR model are compared to measurements [71] | The HSE and NCAR models | -Model predictions of discharge by HSE show that metastable models tended to over-predict measured release rate from the chlorine tank, while flash models tend to under-predict release rates.<br>-The two integral models tested by HSE (DRIFT and PHAST) provide the best fit to the upwind concentration data when they take into account the rainout of liquid from the impinging two-phase jet.<br>-These two models tend to over-predict concentrations slightly, but many measurements may record peak concentrations due to sensor saturation and clouds bypassing the sensors.<br>-A major component of PHAST is the Unified Diffusion Model (UDM), which includes sub-models for two-phase jets, heavy and passive dispersion, droplet rain, and pool spreading and evaporation. |
| 6 | CFD-based simulation of dense gas dispersion in presence of obstacles [72] | -Most commonly used models: SLAB, HEGADAS, DEGADIS, HGSYSTEM, PHAST, ALOHA, SCIPUFF, TRACE<br>-CFD-based models | - They cannot consider the effect of obstacles in the path of the scattered environment<br>-CFD-based models:<br>1. Realistic estimation of the consequence of accidental loss of containment<br>2. Its ability to take into account the effect of complex terrain and obstacles present in the path of dispersing fluid. |

### 4.4. Recent advances in consequence modeling software development

FDS software is a CFD model to investigate and simulate the flows caused by fire, especially the distribution of smoke and temperature. This software can be used for Flows, Smoke transport, Gas transport, Fire spreading, Sprays and cooling, Suppression, and Human behavior [73–75]. This software solves the Navier-Stokes equations as quickly as possible with an emphasis on smoke movement and heat transfer from fire [76]. Various studies of this software have been carried out in tunnels, fire extinguishing systems, buildings, and various process industries [76–79]. Due to the emergence of newer software in the field of outcome modeling such as FDS, it is recommended to make necessary comparisons in this field in future studies, because some studies that have used FDS software have also accused PHAST and ALOHA of overestimation. The CFD model tested by HSE has the advantage of resolving the complex of the high-momentum jet and cloud conduction between Conex containers in the near field [71]. However, it requires long computer run times and there are uncertainties when simulating far-field dispersion beyond about 1 km, due to errors in the boundary layer profiles that occur beyond this distance. The CFD model accounts for the initial momentum and turbulence generated by the impinging jet, while the DRIFT and PHAST models use a simpler low-momentum source [71].

Other software is also used recently for consequence modeling, and below we will mention some examples of their recent applications. In a study conducted by Lyu et al. (2022) with the aim of Investigation and modeling the LPG tank truck accident in Wenling with EFFECTS and ALOHA software in China; The results showed that the gas cloud distribution simulated by the SLAB model almost corresponds to the major part of the heavily damaged area. In this study, the TNO multi-energy method and ALOHA provided fairly consistent predictions with the actual damage distribution when the models used a specific confined explosive mass [80].

Another study was conducted with the aim of Comparison of FLACS and BASiL Models for leak analysis with CFD FLACS software in 2022. Out of 24 leakage cases, the results of FLACS and the BASiL model agreed in 18 cases, and the BASiL model underestimated the safety zone distance in three cases compared to FLACS [81]. In Liu and Wang's study, MATLAB and FDS software were also used for fire simulation [82]. In the study of Liu et al. (2018), ALOHA results were also used as input to FDS software. In this way, ALOHA software was used to calculate the leak source strength of the cryogenic ethylene tank, and the calculation results were provided to FDS software to set up the model [83]. There is other software in the market for modeling the outcome of process industries, which is recommended to perform analytical comparisons and appropriate review studies in the field of their best use in future studies.

## 5. Conclusion

The results of reviewing 40 articles in this systematic review showed that various quantitative and qualitative methods have been used to identify scenarios. Also in Iran, two software were most used in consequence modeling studies. The results showed that examining a scenario with different software will bring different results, the main reason for which can be rooted in the default calculations and formulas of that software. PHAST and ALOHA software did not have the necessary ability to provide correct results at low concentrations and there was no equal match between the results of the two software. PHAST software has also provided more accurate results than ALOHA over longer distances in stable and relatively stable weather conditions. These two methods can be used to predict accidents and changes in the structure of industries. It is also suggested in future studies to compare PHAST and ALOHA software with other software such as FDS by examining several similar scenarios.

## Author contribution statement

Mostafa Pouyakian: Conceived and designed the experiments; Wrote the paper.
Maryam Ashouri: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.
Shaghayegh Eidani: Analyzed and interpreted the data.
Rohollah Fallah Madvari: Contributed reagents, materials, analysis tools or data.
Fereydoon Laal: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

## Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Data availability statement

Data included in article/supp. material/referenced in article.

## Declaration of interest's statement

The authors declare no conflict of interest.

## Acknowledgment

The present study was reviewed by the ethics committee of Birjand University of Medical Sciences and has an ethics code of IR. BUMS.REC.1401.158 number (tracking code: 6010).

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