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Applications of resilience engineering principles in different fields with a focus on industrial systems: A literature review

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A R T I C L E I N F O

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A B S T R A C T

This paper reviews literature that addresses applications of resilience engineering principles to various fields. Recently the concept has attracted great attention from a technical and industrial perspective. The primary focus of this paper is to review the resilience engineering applications to industrial systems with the purpose of applying them to the chemical industry. A systematic review is performed to classify peer-reviewed journal papers that are associated with resilience engineering applications into three categories: industrial systems, ecological systems, and interlinked systems. The literature in the category of industrial systems is further divided based on the type of approaches such as field studies, case studies, methodologies, and mathematical modeling. After thoroughly analyzing the literature, four key research areas are identified: Considering socio-technical factors for resilience assessment efficiently; Inculcating the possibility of multiple disasters in resilience assessment; Design optimization for resilience enhancement; Efficient restoration strategies. All these research areas have not been explored exclusively for chemical facilities to a great extent. It is concluded that if these research areas are addressed appropriately, it would help in triggering the research pertaining to the application of resilience engineering principles in chemical facilities.

Author statement

Bhushan Pawar: Methodology, Data curation, Formal analysis, Writing – original draft. Sunhwa Park: Formal analysis, Writing – review & editing. Pingfan Hu: Validation, Writing – review & editing. Qingsheng Wang: Resources, Project administration, Supervision

1. Introduction

Over the last decade, many attempts have been made to apply resilience engineering principles for making systems resilient against disturbances in various domains. An increased number of catastrophic incidents have encouraged our society to apply resilience approaches in a wide range of engineering fields. Therefore, the concept of resilience has gained an ever-increasing order of attention from the scientific community recently.

Being a new evolving discipline in engineering, there has been a lot of work done regarding defining resilience from an engineering perspective. There are numerous definitions available in the literature and all of them have evolved with time. Jain et al. (2019b) compared some of the early definitions of resilience belonging to different research areas from 1973 and demonstrated how they were modified to understand the concept of resilience from a technical standpoint. This transition in the definitions highlights the interest of researchers in the concept of resilience. One of the most straightforward definitions for resilience is the ability of a system to absorb any changes or disturbances. To lower the impact of disturbances on the system performance, it should be able to absorb the disturbances efficiently. Higher absorption efficiency implies higher resilience (Fraccascia et al., 2017). Generally, resilience is defined as the ability to bounce back when hit with unfavorable conditions (Dinh et al., 2012). However, there is no universally accepted definition because the term "resilience" has been defined by researchers in ways that are specific and suitable for their research fields. Therefore, there are multiple definitions of resilience which are available in the literature.

1.1. What are resilience engineering principles?

The main objective of this paper is to review the research work related to the application of resilience engineering principles to

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industrial systems with the purpose of applying them to the chemical industry. The motivation for this work is the scarcity of literature related to the application of resilience engineering to chemical plants.

Resilience engineering principles are factors which are conducive to the resilience of industrial processes. The resilience of an industrial process will depend on the extent to which these principles are addressed in the process. Researchers have identified several resilience engineering principles and defined them in different ways. Six resilience engineering principles that contribute to the resilience of any process were identified by Dinh et al. (2012). They are: Flexibility; Controllability; Early Detection; Minimization of Failure; Limitation of Effects; Administrative Controls/Procedures. These principles are explained briefly below.

- Flexibility

Flexibility is the ability of a process to keep its output variation within a specified range when the input changes due to a disturbance within a defined range. Increase in flexibility of a process makes it more resilient to disturbances.

- Controllability

A process is controllable if its output parameters can be controlled and set to target points within a certain time when there is an unexpected deviation in input parameters. Flexibility and controllability are different because flexibility deals with steady state whereas controllability refers to dynamic state of the process.

- Early detection

Early detection of disturbances comes into picture when all the preventive measures fail to avoid the disturbance. This principle is important because an undetected disturbance can often lead to disasters.

- Minimization of failure

Minimization of failure refers to implementing preventive measures to avoid disasters.

- Limitation of effects

In case of an unavoidable disastrous event, it is important to ensure that the loss to the process system is minimum. This principle is used for setting up strategies to limit the consequences of a disastrous event.

- Administrative controls/procedures

Some disturbances cannot be detected and prevented using the principles mentioned earlier. This principle helps in developing management systems such as training program for workers, updating operating procedures, etc. for dealing with such disturbances.

Besides these, researchers have determined several other principles that can affect resilience of industrial processes, such as awareness of workers, learning ability, training, and job fatigue (Jain et al., 2018a; Righi et al., 2015).

1.2. Resilience of chemical plants

Chemical plants comprise of processes which operate in extreme temperature and pressure conditions. Therefore, they are highly susceptible to natural disasters as well as disasters caused by human errors. Chemical plants are particularly prone to accidents because of the toxic or flammable nature of the chemicals involved in the processes. A natural disaster like an earthquake or hurricane can trigger a catastrophic incident at a chemical plant. Such incidents are known as Natural-Technological (Na-Tech) disasters. Chemical industry has witnessed several catastrophic incidents in the past. For instance, the Na-Tech incident with organic peroxides stored in cooled trailers at the Arkema plant after hurricane Harvey in Texas (O'Connor et al., 2019). Due to the power outage after the hurricane, the cooling facility stopped working. It resulted in an exothermic decay of the chemicals leading to a fire accident. These types of incidents occur frequently in chemical plants because of the complex network of pipelines and storage tanks. Any abnormality in the functioning of one process unit of a chemical plant can affect another process unit and lead to a "domino effect". Therefore, for minimizing the economic and physical loss, it is important to enhance the resilience of chemical plants to external disturbances.

A resilient design is necessary to ensure minimal loss of functionality when a disaster occurs. There are very few studies available which are related to the designing of a chemical plant from a resilience engineering perspective. Cincotta et al. (2019) designed a resilience based optimal firefighting strategy to avoid domino effect in storage tanks. There are many resilience assessment frameworks available. Caputo et al. (2020) proposed a methodology for resilience assessment in the event of a seismic hazard or earthquake. The methodology is based on estimating capacity lost in a process system after the disaster has occurred. Mebarki (2017) proposed a similar methodology using a similar model for resilience assessment of industrial plants against tsunamis in coastal region.

One of the key factors responsible for disturbances in smooth functioning of a process plant is human interaction. Several studies reviewed in this paper have emphasized the importance of human factors in resilience enhancement. Human factors such as ignorance, lack of training or experience, lack of communication, and work fatigue can be responsible of accidents. These factors also play a critical role after a disastrous event has occurred. For instance, communication and experience are important factors for getting the plant back to its normal working condition. If there is no proper communication between the workers and management officers in a plant, it would be difficult to restore the plant after the disaster has occurred. Therefore, researchers have proposed resilience assessment frameworks which can help in determining which aspect of human factors need to be improved for smooth functioning of industrial processes. These frameworks are reviewed in section 3.4. Methodologies proposed by Caputo et al. (2020) and Mebarki (2017) claim to be applicable to any industrial system. However, they do not account for the intricacies of a chemical plant. They fail to address the interdependent nature of chemical process units and human factors. Also, these methodologies are specific to one type of natural hazard. In the past six years, researchers have been exploring the use of statistical tools such data envelopment analysis, sensitivity tests, and reliability tests for analyzing the effect of human factors on resilience of an industrial system. We have reviewed papers that proposed resilience assessment frameworks using such statistical tools in section 3.4. These frameworks can prove to be instrumental in accounting for the human factors involved in a chemical plant.

1.3. Three phases of resilience

Fig. 1 shows three phases that resilient industrial systems go through during external disturbances. Research associated with resilience of industrial systems was found to have three common themes: absorption, adaptation, and restoration (Jain et al. 2018a, 2019b; Li et al., 2019; Tong et al., 2020). For instance, consider a process system with an input and output. Absorption refers to the ability of the system to absorb external disturbances without any significant deviation in the output. Adaptation comes into effect after the absorption phase fails to absorb external disturbances and when the output of the system deviates significantly from its normal value. During the adaptation phase, the dynamics of the system are adjusted in such a way that it adapts to the external disturbances and there is no further deviation in the output. After the system has adapted to external disturbances, the restoration

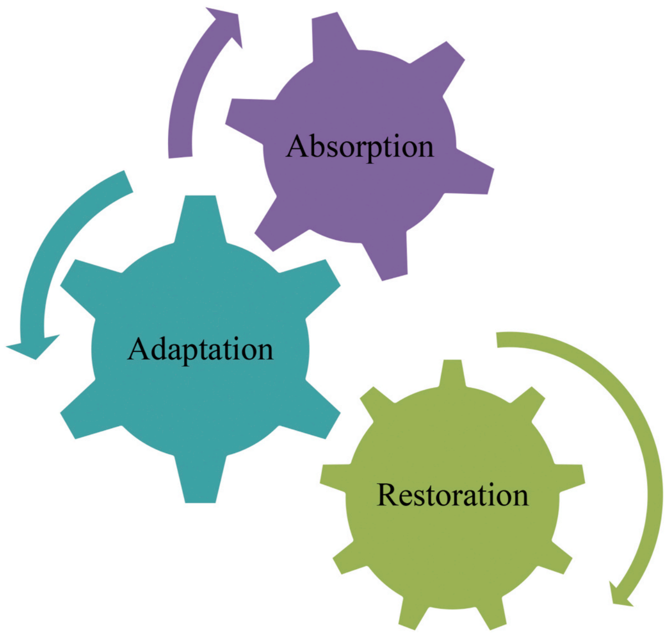

Fig. 1. Three phases that comprise resilience of an industrial system during external disturbances.

phase comes into effect to restore the system to its normal state. These three phases together comprise the resilience action of any engineering system. After reviewing the literature associated with application of resilience engineering in industrial systems, it was found that resilience engineering, in general, refers to implementing various engineering tools to enhance the effectiveness of these three phases. As shown in Fig. 1, the three phases always follow the same order, first absorption followed by adaptation and then restoration. Each of these three phases are essential for the resilience of the system, lack of one or more of these phases would render the system highly vulnerable to disasters. A system experiencing external disturbance does not necessarily go through all the three phases. If the absorption phase can absorb the disturbance while maintaining the output within an acceptable range, then there is no need of adaptation and restoration. Various measures and strategies can be implemented for improving the effectiveness of these phases. Most of the times, a measure proposed to implement one phase also helps in implementing the other two phases. This is because of the interdependent nature of the three phases as shown in Fig. 1. For instance, if most of the external disturbances get absorbed during the absorption phase, then it would get easier to adapt and restore the system to its normal condition.

1.4. History of research in resilience engineering

Classifying research associated with resilience based on objectives and purposes enables us to properly understand previous attempts and the way research has evolved. Several researchers classified research associated with resilience in various ways to portray different perspectives. For instance, Woods (2015) demonstrated that different technical approaches for defining resilience can be classified into four concepts: resilience as restoration from a trauma, resilience as a synonym for robustness, resilience as the opposite of brittleness, and resilience as sustainable network architectures that can adapt to future surprises. In contrast, after reviewing 237 studies published between 2006 and 2014 related to resilience in different domains such as healthcare, construction, and railways, Righi et al. (2015) grouped them based on their research areas. They identified six research areas for resilience engineering across all the domains: theory of resilience engineering, identification of resilience, safety tools, analyzing accidents, risk assessment, and training modules. They concluded that research areas related to "theory of resilience engineering" accounted for about 52% of the 237 studies, which indicates that the major focus of research was on exploring resilience engineering conceptually and theoretically rather than its application (Righi et al., 2015).

Fig. 2 depicts the timeline for research related to resilience engineering. In 1982, the term "resilience" was coined for the first time from a chemical engineering perspective while attempting to solve a resilient heat exchanger network problem (Marselle et al., 1982). From 1982 to 2009, the concept of resilience was explored in many different fields such as cognitive sciences, health care, and finance. During this period, the concept of resilience was investigated from a technical or engineering perspective as well. For instance, Vidal et al. (2009) demonstrated how different teamwork strategies could help in enhancing the resilience of complex systems that involve several workers coordinating with each other. However, the resilience engineering applications in industrial processes were explored during the time from 2010 to 2014. Principles and factors that affect the resilience of an industrial process were identified by Dinh et al. (2012). Shirali et al. (2012) illustrated several challenges in building a resilient industrial process: lack of experience in resilience engineering, out-of-date procedures and manuals, and economic problems. Later in 2014, new research topics associated with chemical industries' resilience were explored through multiple studies. For instance, the framework addressing the gap between work as imagined by managers and the workers proposed by Azadeh and Salehi (2014). This framework was found to be instrumental in reducing the efficiency gap between workers and managers in a petrochemical plant.

1.5. Need for a systematic review

During 2015 to 2020, as shown in Fig. 2, there was a significant surge in research related to the resilience of industrial processes. There was also an increase in the usage of mathematical modeling tools for assessing resilience of industrial processes (Macuzić et al., 2016) and considering socio-technical factors like interaction amongst workers for resilience assessment (Azadeh et al., 2016). Therefore, we classified and analyzed the research papers published during 2015–2020 to find the research areas in which application of resilience engineering is dominant.

As a holistic view of resilience applications' research development between 2015 and 2020, we classified the research papers into three categories. These selected categories—industrial systems, interlinked systems, ecological systems—were derived from Fraccascia et al. (2017) because these categories are conventionally considered as exclusively independent based on their characteristics. However, Fraccascia et al. (2017) explained how these three types of systems are dependent on each other in the form of a symbiosis. Symbiosis refers to the condition where the waste or by products of one industry could be used as an input or raw material for another industry. This condition is beneficial because it reduces the constant stress on environment for raw materials and energy production. It leads to an interdependent system of industries which implies that any disturbance in the functioning of one industry would affect the production capacity of other dependent industries and thereby disrupting their supply chains with the consumers. To avoid this catastrophic event, it is necessary to address the resilience of all the three types of systems. Therefore, we have adopted a similar classification of systems and reviewed the research on resilience engineering application for the three types of systems. Although resilience engineering application in ecological and interlinked systems is beyond the scope of this paper, we have briefly reviewed them in sections 4 and 5.

Industrial systems are process systems which include industrial processes such as manufacturing, operations, and management. Interlinked systems consist of sub-systems which are highly interdependent on each other in a complex way. Studies on the resilience of interlinked systems mostly deal with financial systems like stock market, food

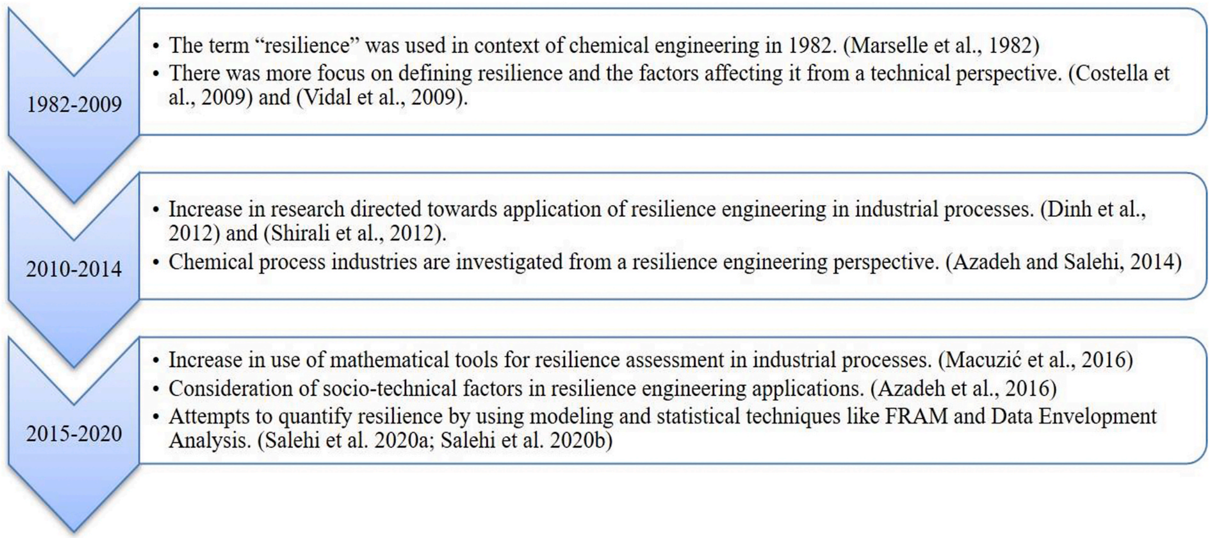

Fig. 2. Timeline for research progress in investigating resilience from an industrial systems perspective.

production and supply chains. Ecological systems are systems that get affected by disturbances in ecological factors such as environment, population, and climate. These three categories are explained in detail in sections 3, 4 and 5 of this paper.

The application of resilience engineering principles to chemical industries and processes remains a relatively unexplored research area as compared to other areas such as construction, health care, and urban planning. The aim of this work is to review resilience engineering applications in industrial processes and identify key research areas. Therefore, a systematic review of the work being done from 2015 to 2020 in resilience engineering applications to industrial processes is performed. These research areas have been investigated to apply them in chemical industries specifically. There is a major gap in research pertaining to the application of resilience engineering to the chemical industry. This review specifically addresses this gap by studying literature available as of October 31, 2020. The references are analyzed for their goals of research and then classified depending on their similarities in approaches as well as their shortcomings. A systematic review is used to classify the references and then identify some key prospective research areas that would help in filling up research gaps.

Ranasinghe et al. (2020) performed literature reviews on resilience engineering and explored the resilience indicators that have been identified in the literature across 11 high risk industries. They concluded that four indicators were most associated with resilience: top-management commitment, awareness, learning, and flexibility. Whereas Patriarca et al. (2018) explored the studies on resilience across different fields such as engineering, social sciences, computer science, medicine, chemical engineering, business, management and accounting, environmental science, and decision sciences. They performed temporal analysis on the studies to find out the five prominent clusters in resilience research: the need of resilience engineering, resilience engineering for modeling, defining and exploring resilience engineering, reflecting on resilience engineering, resilience engineering and improvisation. The literature review performed in our paper is different in the way it identifies the key research areas in resilience engineering. Our study identifies some key research areas in resilience engineering as well as the approaches that have been taken to investigate those research areas. We employ a classification method based on the type of system under consideration and the approach taken by researchers for investigation. Therefore, our study will help the readers to learn about the key research areas in resilience engineering as well as the different approaches and techniques being used in resilience research. It will help the researchers to focus on the key research area of their choice and give them a guideline for approaching that area based on past studies. Moreover, we have performed a review of the studies that find application in chemical plants or may find application in chemical plants in future. Therefore, we have particularly focused on industrial systems because literature related to application of resilience engineering in chemical plants is scarce. We conclude with some suggestions for future work in resilience of chemical plants based on the review of previous research done for industrial systems.

2. Methodology

The motivation for this work is the lack of literature related to the application of resilience engineering to chemical plants. Therefore, we searched the databases for articles related to resilience and chemical engineering. Fig. 3 illustrates several steps taken while selecting appropriate papers to achieve the objective of this paper. The ScienceDirect and Web of Science databases were used to retrieve peer journal papers, conference papers, and book chapters related to resilience engineering. The keywords used for searching were "resilience engineering" and "resilience and chemical" to obtain the bibliographic data and a total of 30,634 results were extracted from the ScienceDirect database. Similarly, the keyword used for searching on the Web of Science database was "resilience engineering" along with a filter which restricted the results to "Engineering Industrial" domain. We tried searching the words "resilience engineering" and "chemical" on Web of Science database, but the results obtained did not match the selection criteria. A total of 179 results were obtained from Web of Science database. We targeted studies which have been published since 2015 but we also included some high-quality studies prior to 2015 related to resilience engineering.

2.1. Selection criteria

We selected studies for review based on the following two criteria:

- Studies included applications of resilience engineering principles in industrial systems, interlinked systems, and ecological systems.
- Studies had prospective applications in chemical plants.

Finally, a total of 122 papers were sorted out manually after abstract reading and excluding the duplicates from both databases.

Studies were rejected based on the following two criteria:

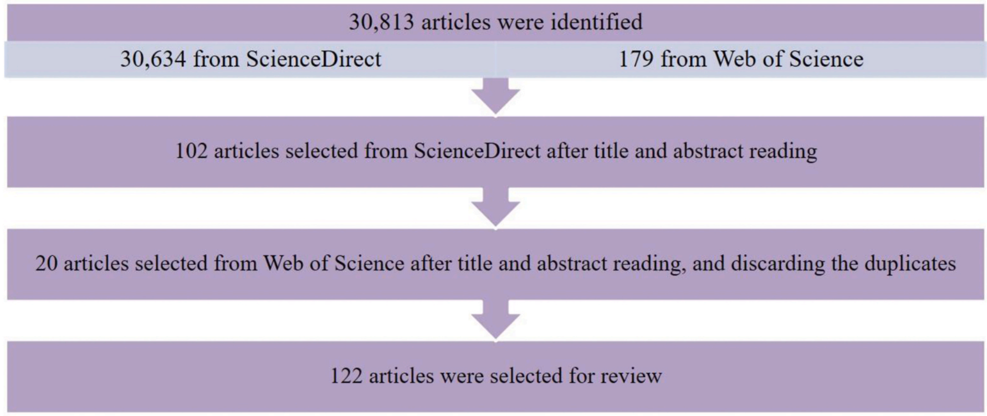

Fig. 3. A flow chart depicting the methodology of the literature review.

- Studies were related to systems other than industrial systems, interlinked systems, and ecological systems.
- Studies were published in a language other than English.

2.2. Classification

Fig. 4 illustrates the categorization of the selected 122 papers through multiple steps. First, we classified them into three categories: Applications in industrial systems; Applications in ecological systems; Applications in interlinked systems. Such classification was adopted from Fraccascia et al. (2017) because they reviewed literature related to resilience engineering from an industrial symbiosis perspective as explained earlier in section 1.

Resilience is a new concept and there are multiple ways to approach it such as surveys, conducting interviews with the employees, using data analytics, fuzzy logic and many more. Research associated with applications in industrial systems is further divided into four sub-categories based on their type of approach towards researching resilience: field studies, case studies, methodologies, and mathematical modeling. Field studies are carried out by conducting interviews with the workers and managers. Case studies, as the name suggests, make use of a real or hypothetical case to support their hypothesis. Methodologies are a set of paradigms and frameworks designed for making the systems more resilient whereas mathematical modeling takes more of a probabilistic approach towards quantifying resilience numerically. This type of sub-classification was performed because we observed a pattern in the approaches used by the researchers. Every approach had a common theme of research. For instance, field studies involved research related to the impacts of socio-technical factors on resilience and hazard analysis from a resilience perspective. Case studies involved investigating past incidents or using hypothetical cases for proposing new resilience assessment frameworks whereas mathematical modeling involved use of mathematical tools and algorithms. After exploring these common themes, we were able to identify four major research areas associated with resilience engineering application in industrial systems. Therefore, we reviewed the studies by grouping together similar types of approaches. Some papers in this review address a common research idea or follow a common approach of investigation. We have elaborated some of these papers belonging to the industrial systems sub-categories in more details because they were important and helpful in explaining the common research idea more efficiently as compared to other papers. We have followed this approach for all sub-categories.

3. Applications in industrial systems

Industrial systems are process systems which include industrial processes such as manufacturing, operations, and management. They consist of complex machinery, manufacturing units, workers, etc. These systems are expected to be functional at maximum efficiency irrespective of internal or external disturbances which is one of the important reasons as to why resilience has gained popularity amongst the engineering community. As the production units manufacture

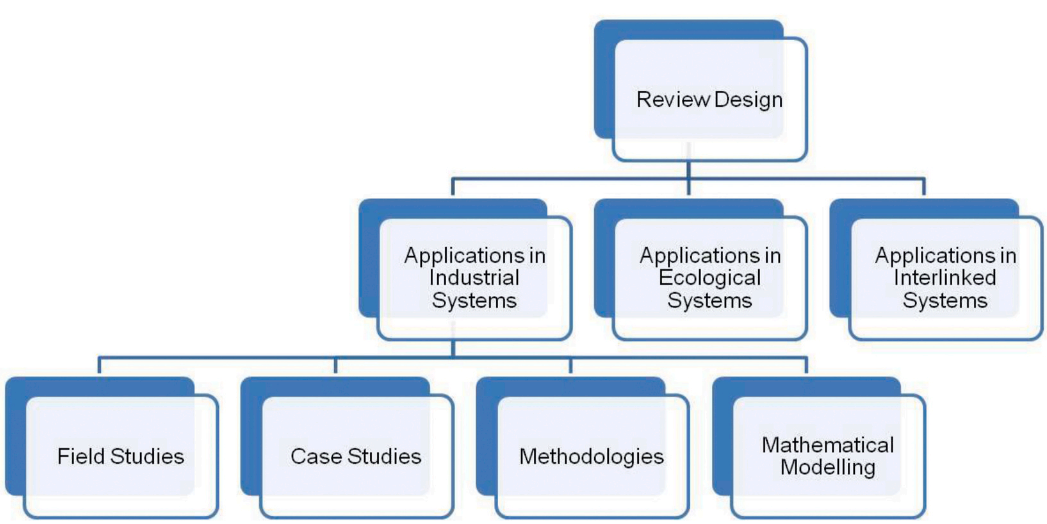

Fig. 4. Flow chart depicting the classification of papers according to the review design.

massive amounts of commodities to suffice the needs of the population, they should be able to absorb these disturbances and continue functioning. As mentioned earlier, we have classified and compiled the research papers in this category based on the type of approach as: field studies, case studies, methodologies, and mathematical modeling.

3.1. Field studies

A field study involves carrying out in-depth surveys, obtaining feedback from the employees, performing literature reviews, identifying possible sources of disturbances, and then suggesting measures to make the plant more resilient. One of the advantages of this kind of approach is that it tends to rectify any disturbance that might occur right from the shop floor level to the higher management level. This kind of studies is useful for analyzing factors that affect resilience of a system and cannot be measured numerically. For instance, socio-technical factors such as teamwork and communication are critical for resilience, but they cannot be measured directly. Field studies prove to be instrumental in this regard because the researchers can get an idea about the working habits of the staff by conducting interviews and surveys.

Ten out of the 16 field studies reviewed explored socio-technical factors and human interaction as important aspects for enhancing resilience (Asadzadeh et al., 2015; Dinh et al., 2012; Enjalbert and Vanderhaegen, 2017; Jain et al., 2018b; Pasman, 2015b; Pasman et al., 2018; Shaw et al., 2014; Shirali et al., 2012; Van Der Beek and Schraagen, 2015; Vidal et al., 2009). Socio-technical factors have a social and technical aspect that can disrupt the process. These factors are a result of the social habits of the workers, for example, an unskilled plant operator, a worker who takes incorrect measurements of process parameters, a worker having superstitious beliefs and many more. Human interaction refers to factors which can cause a disturbance in a process due to lack of proper communication between the managers and the workers. These factors are often overlooked while addressing other Na-Tech events. However, there have been numerous instances of accidents at chemical facilities which were caused not only because of natural calamities but also human negligence. Therefore, it is necessary to analyze the impact of socio-technical factors on resilience.

To achieve this goal, it is important to first identify some of the critical socio-technical factors. Once they are identified, then the researchers can propose some strategies to cope with those factors. Identification of some of the socio-technical factors had been accomplished by conducting on site surveys and interviews. For instance, Shirali et al. (2012) analyzed and identified the challenges that might occur while implementing concepts from resilience engineering to a chemical plant. Interviewing personnel and carrying out on site studies led to the conclusion that the main challenges could be classified into 9 categories as lack of explicit experience about resilience engineering, intangibility of resilience engineering level, choosing production over safety, lack of reporting systems, religious beliefs, out-of-date procedures and manuals, poor feedback loop, and economic problems. Six out of these 9 categories are associated with socio-technical factors: lack of explicit experience about resilience engineering, intangibility of resilience engineering level, choosing production over safety, lack of reporting systems, religious beliefs, and poor feedback loop. These six categories have socio-technical aspects because they are dependent on social behavior and technical awareness of the workers. Such classification and characterization are instrumental in identification of socio-technical issues. However, in this study, only 48 employees were interviewed, and direct observation was carried out only for a few days. Even though the results for this study seem promising, their reliability could be questionable due to a smaller number of data points. Shirali et al. (2012) considered the socio-technical factors to some extent.

There were multiple studies in the field studies category which addressed the issue of identification of socio-technical factors. For instance, Van Der Beek and Schraagen (2015) investigated the effect socio-technical factors on teamwork. They proposed a questionnaire for developing the resilience of a team called ADAPTER (Analyzing and developing adaptability and performance in teams to enhance resilience). They identified four socio-technical factors that affect the resilience of a team of workers during a disaster: monitoring, learning, response, and anticipation, as well as relation-oriented qualities like leadership and cooperation with other teams. However, the quality of data obtained by using questionnaire can be questionable in contrast to that obtained through interviews where researchers have a face to face conversation with individual workers.

After identification, the focus should be on mitigation of hazards due to socio-technical factors. Vidal et al. (2009) performed identification and proposed mitigation strategies for enhancing the resilience of a team. The performance of all industrial systems is dependent on the performance their workers collaborating as one big team. Therefore, Vidal et al. (2009) explored teamwork as a socio-technical factor extensively in their field study. A unique support system design which facilitates improved coordination in teamwork activities was proposed by Vidal et al. (2009). They illustrated the different operation modes of a nuclear plant and then went onto focus on the cooperation mode of operation. They proposed different strategies for efficient communication amongst team members. Communication is a socio-technical factor that plays a key role in efficient functioning and control of the plant in both undisturbed and disastrous situations. Therefore, enhancing communication amongst team members will also enhance their capacity to perform during absorption, adaptation, and restoration phases in the event of a disaster. This implies that efficient communication is critical to the resilience of a system. Fig. 5 shows a depiction of the proposed strategies that can enhance communication and thus, the resilience of a system. Although Vidal et al. (2009) proposed the design specifically in the context of nuclear power plants, this concept can be extended to chemical plants too. Hence, we took a closer look at all these strategies.

A brief definition for all the above-mentioned strategies is provided below.

- Recognition of intentions

Recognizing intentions helps in understanding the goals of the team members and it can be achieved by actively listening to the communications with the other team members, paying attention to various physical parameters of the plant and also by noticing the behavior of the team members. These practices can help in avoiding errors in plant functioning. If looked upon from a socio-technical perspective, it can also help in avoiding damages due to human errors. For instance, noticing a team member's nervousness due to lack of information will enable other team members to provide essential information to the nervous team member, thus avoiding any error.

- Distributed cognition

The information needed to control and operate a plant is distributed over numerous redundancies. Such redundancies are useful to avoid any error and distribute essential information to all the team members. There are two types of redundancies:

  - o Informational redundancies

Team members can have information transmitted through communication with each other or through control panels and indicators in a plant. This is helpful because any discrepancy can be resolved by verification and replacing the faulty indicators.

  - o Human redundancies

Team members can share information about their respective tasks so that in case of an emergency any member of the team can carry out the task of any other member of the team.

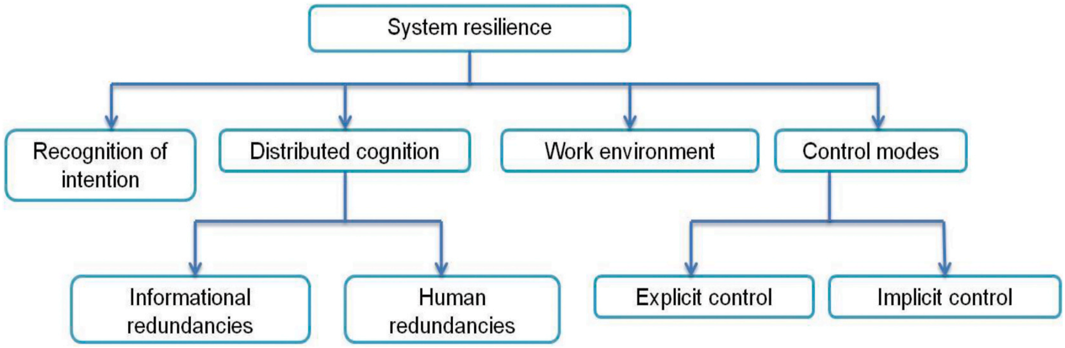

Fig. 5. Strategies for enhancing resilience of a system involving a team of workers according to Vidal et al. (2009).

- Work environment

A healthy work environment is essential along with a good cognitive system to ensure smooth and safe functioning of the plant. The work condition must be well equipped with up to date safety measures, instruments for measuring physical parameters of the plant and some communication equipment like radio or intercoms. This will ensure that all the team members are aware of the ongoing situation of the plant.

- Control modes

Control modes are necessary for smooth functioning of the team by establishing control over the way in which commands are informed to the team members. There are two types of control modes which are used depending on the type of system and situation.

o Explicit control

This control strategy is more direct and involves an explicit control from a superior team member to the concerned member in the form of a direct communication. In case the task needs more than two members, then each member is liable to explicitly report their activities to their superior as well as each other in the form of a close control loop.

o Implicit control

This control strategy does not involve direct control over team members. They are not bound by a close control loop, instead they have the autonomy to act based on their experience and self-realization during certain situations.

A combination of the above-mentioned strategies could be instrumental in enhancing the resilience of a chemical facility where teamwork is critical as in the case of a nuclear plant. For instance, Shirali et al. (2012) identified lack of reporting system and poor feedback as some of the challenges in building resilience engineering. Such challenges are often encountered in chemical plants as well. These challenges could be addressed by implementing distributed cognition and explicit control strategies. This would help in improving communication between operators and managers in a chemical plant and therefore increase its resilience to disastrous events. However, socio-technical factors are more crucial for nuclear plants as compared to chemical plants and other process industries because of the tremendous extent of damage caused in a nuclear disaster. The work done by Vidal et al. (2009) is important because it is one of the few works that not only identifies socio-technical factors but also proposes strategies for mitigating the hazards of those factors. Whereas Shirali et al. (2012), Van Der Beek and Schraagen (2015) only address the issue of identification of socio-technical factors.

Restorative strategies for chemical plants are relatively unexplored in literature. Li et al. (2019) explored absorptive and restorative measures that could be used for resilience assessment of a process system. They proposed a new risk assessment framework which was derived from a conventional hazard analysis method. The only difference is that their framework considers absorptive and restorative measures during hazard analysis which are usually ignored in a conventional hazard analysis. Such framework can be extended to chemical plants by performing surveys to estimate the action taken by workers and managers after a disaster has occurred. By using the data obtained through surveys, an action plan could be proposed to effectively restore the chemical plant to its normal working condition. There are many studies reviewed later in this paper which use surveys for resilience assessment of process industries, but they are mainly focused on adaptive and absorptive strategies. On the other hand, Cabrera Aguilera et al. (2016) and Ehlen et al. (2014) used modeling tools for resilience assessment. Cabrera Aguilera et al. (2016) modelled performance of oil spill response teams using Functional Resonance Analysis Method (FRAM) which is a popular modeling tool used by many researchers who work on resilience engineering. It is generally used for modeling complex systems which depend on socio-technical factors. They concluded that performance variability of response team was a result of intentional adjustments made by operators in their duties to achieve required work efficiency. Nemeth and Herrera (2015) performed a review on how resilience is perceived across different fields of studies and what future developments can be expected in research related to resilience. Okoh and Haugen (2015) explored the effect of maintenance activities on resilience and robustness of process industries. They concluded that maintenance could improve the adaptive, absorptive, and restorative abilities of process industries. The operational links between maintenance and production activities can improve robustness and resilience of an organization. Such operational links are also present in chemical plants. For instance, carrying out maintenance activities for process units such as distillation columns, heat exchangers or performing fire safety mock drills, will help in improving the resilience of chemical plants. The links represent means by which maintenance can interact in harmony with other units for the purpose of improving organizational robustness and resilience. Ehlen et al. (2014) modelled the effects of a hurricane on the supply chain of a chemical plant using Agent based modeling. Their modeling approach was instrumental in understanding various aspects of resilience of a chemical plant such as interaction between different chemical process units, effect of disasters on demand and supply of chemicals, and economic loss.

Even though field studies provide innovative solutions for making a system resilient through analyzing socio-technical factors, they have a drawback. Most of the strategies for identification and mitigation of socio-technical hazards proposed by the field studies are dependent on obtaining feedback through interviews or questionnaires. If a particular industrial system does not have an experienced and large human workforce, then the feedback obtained through these techniques might not be sufficiently dependable. Fewer work forces would imply less reliable feedback through interviews or questionnaires. However, these strategies would be more helpful for huge and well-established industrial systems with larger and more experienced work force.

3.2. Case studies

Case study is often performed to verify any new research because it serves as a concrete evidence to support the new proposed ideas (Amodeo and Francis 2019; Azadeh and Salehi 2014; Hu et al., 2015; Labaka et al., 2015; Lay et al., 2015; Mebarki et al., 2014; Mendonça and Wallace 2015; Saurin et al., 2014; Sonnemans and Körvers 2006). Case studies span variety of topics related to a research area. Some of the important topics encountered while reviewing case studies related to the application of resilience engineering include analyzing work actually performed by workers and work imagined by managers, factors affecting resilience of a system, and strategies for embedding resilience engineering principles. The underlying key concept that is common in all these topics is the role of socio-technical factors in the resilience of industrial systems. Therefore, we reviewed these case studies to study the methods used by researchers for identification and mitigation of hazards caused due to socio-technical factors.

The perception of work being performed by managers in any chemical plant is ideal. They often think of workers as a part of the industrial machinery that would follow all the rules and protocols ideally without any discrepancy. However, this misconception is one of the most important reasons for the occurrence of disasters in chemical plants. There is always a certain inconsistency between work as imagined by the managers and work actually performed by the workers. More the inconsistency, lower is the resilience of the system to disasters. This is because if the workers do not follow the protocols exactly as dictated by the managers during the absorption, adaptation, and restoration phases, then the system would no longer be resilient. Workers are bound to commit errors in their day-to-day operations because of numerous socio-technical factors. It is necessary to have a holistic framework for addressing these socio-technical factors. This will ensure that the gap between work as imagined by the managers and work actually performed by the workers is the least. Azadeh and Salehi (2014) considered the socio-technical factors of the system while proposing a framework called "Integrated Resilience Engineering (IRE)" framework which was used to calculate the performance efficiency of managers and workers. The framework considered 10 socio-technical factors for evaluating performance efficiency: commitment management, reporting culture, learning, awareness, preparedness, flexibility, self-organization, teamwork, redundancy, and fault-tolerant. Mendonça and Wallace (2015) identified and illustrated socio-technical factors affecting resilience such as flexibility, reliability, and tolerance which are like the factors used by Azadeh and Salehi (2014) in their framework. They proposed a questionnaire that addressed each of these factors and the response from the workers and managers was used to find out which factors need to be improved using statistical methods. Some questions related to each factor from the questionnaire are as follows:

1) Top-level commitment (e.g. Do you feel you have the ability to stop production if safety is at risk?)
2) Reporting culture (e.g. Do you feel comfortable reporting safety issues/problems to your boss?)
3) Learning (e.g. Do you think that the past success the organization experienced is taken as a guarantee for future success?)
4) Awareness (e.g. Do you think all employees know about the safety concerns in this company?)
5) Preparedness (e.g. Do you actively prepare to anticipate future problems, by conducting safety group meetings or workshops?)
6) Flexibility (e.g. Are there human resources (managers, operators, etc.) with multiple skills to deal with sudden accidents?)
7) Self-organization (e.g. If the system faces a problem, does your department have the adequate authority – from the boss – for decision making?)
8) Teamwork (e.g. Do you assist your colleagues, when the workload is high?)
9) Redundancy (e.g. If one of operators of the critical departments of the system–e.g. control room operator – faces a problem, is there any alternative to it?)
10) Fault-tolerant (e.g. If one of the critical components of the system – components, machinery, servers, and software – faces a problem, can the total system continue the work?)

This framework seems promising because Azadeh and Salehi (2014) performed a case study at a petrochemical plant with 115 volunteers (37 managers and 78 workers). They were able to increase the performance efficiency of managers and workers by identifying factors that needed improvement and suggesting appropriate measures. This is the general methodology adopted by all the resilience engineering frameworks. The use of questionnaires is the most common strategy encountered in such frameworks.

The framework proposed by Azadeh and Salehi (2014) analyzed the factors which are internal to an industrial system. They distributed the questionnaire amongst the workers and managers working for a petrochemical plant. But they did not give any consideration to external factors such as government policies, laws, and regulations. In the event of a disaster, such external factors can prove to be extremely beneficial for the resilience of the industrial system. A framework for resilience that considers both internal and external factors was proposed by Labaka et al. (2015). This framework addressed resilience in two ways: Internal resilience, and external resilience. Internal resilience refers to the resilience level of the system itself, whereas external resilience refers to the resilience contributed by external agents such as government, first responders (fire-fighters, police, military, emergency units, etc.), and society. These external agents play a crucial role in the recovery phase of chemical plants. Due to the toxic and flammable nature of the chemicals, it can be exceedingly difficult to restore the plant to its normal working condition just with the help of internal resilience factors, such as teamwork, self-organization, and preparedness. Labaka proposed policies such as government situation awareness and training, first responder training, regulation and law revision and compliance, and societal situation awareness and commitment. All these policies can help in strengthening the external response to a disaster. In this way, the system will become more resilient.

The framework proposed by Azadeh and Salehi (2014) focused solely on internal resilience whereas the framework proposed by Labaka et al. (2015) considered factors affecting both internal and external resilience. Labaka et al. (2015) applied their framework to a nuclear plant as a part of the case study whereas Azadeh and Salehi (2014) used a petrochemical plant for their case study, but both of these frameworks are holistic in nature and can be applied to chemical facilities as well. However, none of these frameworks consider the possibility of sequential multiple hazards.

Training plays an important role in the recovery phase of a chemical plant. All process industries impart safety trainings and perform safety mock drills, but still disasters occur. Therefore, it is necessary to simulate these trainings in a more realistic and interactive way. Saurin et al. (2014) proposed a methodology with five steps for designing a scenario based training from resilience engineering perspective: (a) identification of resilience skills, work constraints, and actions; (b) design of template scenarios, allowing the simulation of the work constraints and the use of resilience skills; (c) design of the simulation protocol, which includes briefing, simulation and debriefing; (d) implementation of both scenarios and simulation protocol; and (e) evaluation of the scenarios and simulation protocol. A scenario-based training will help in simulating a particular disaster scenario and test the skills and mindset of the workers. The data obtained from a scenario based training would be more authentic than the one obtained from a general safety mock drill. This data can be used to formulate more efficient recovery phase plans and policies.

Buckling of storage tanks can occur in petrochemical plants situated in coastal regions. Mebarki et al. (2014) proposed a framework for resilience assessment using fragility curves for storage tanks situated in coastal regions at the risk of tsunamis. Fragility curves were plotted by calculating failure probability against the tsunami wave height. A probabilistic model was used to calculate the failure probability. Buckling effects were considered while calculating the failure probability. Lay et al. (2015) gave a practitioner's experience about the changes in practices and priorities that were made in power plant maintenance to develop the characteristics of a resilient system. Some changes in practices and priorities could also be observed in chemical plants when policies or plans are implemented for resilience enhancement because of changes in operation of plant. Fault propagation is another important aspect of chemical plants. Due to the highly interdependent nature of chemical process units, fault in one unit can propagate a disturbance to other connected units. For instance, consider a reactor jacketed with a cooling water pipeline. A change in temperature of cooling water pipeline will cause a disturbance in reaction occurring inside the reactor. If the reaction is highly exothermic, then there is a chance of fire accident. Therefore, it becomes necessary to analyze fault propagation in chemical plants. Hu et al. (2015) proposed a hierarchical fault propagation model (HFPM) which is used for analyzing the fault propagation behavior of a process and estimate its resilience. The model involved two steps: the first step is static analysis where the interdependencies of system structure are plotted as a network, the second step is dynamic analysis for fault evolution mechanism where different fault propagation scenarios are analyzed. Depending on the fault propagation behavior, the resilience of the system can be judged qualitatively. If the faults propagate quickly, then the process system is less resilient.

Another important aspect of recovery phase of a chemical plant is learning from the outcomes of the disaster. It is necessary to update the accident control mechanism to avoid the disruptions that caused the disaster in future. However, there have been many instances where the managers and operators fail to notice those disruptions and instead, they invest heavily in new safety protocols and equipment. This can cause a recurrence of the same disaster later in future. Sonnemans and Körvers (2006) analyzed several industrial accidents and concluded that in majority of the cases, repeated disruptions, can be identified as precursors or early warning indicators to disasters. Usually these disruptions get neglected because they do not appear to be severe and later lead to a disaster.

3.3. Methodologies

This category of papers includes methodologies that deal with specific issues such as advanced data gathering for resilience assessment (Patriarca et al., 2019), using process control methods for resilience enhancement (Como 2017; Lamnabhi-Lagarrigue et al., 2017; Su et al., 2018), risk assessment (O'Connor et al., 2019), resilience of interdependent systems (Ouyang and Wang 2015) and multi-disaster situation (Pescaroli et al., 2018). Papers in this category might overlap with case studies because many proposed frameworks are usually verified by implementing them in a case study. Some of these papers are analyzed briefly below.

Risk assessment is a critical component for ensuring safe functioning of a chemical plant. It helps in identifying potential threats that can disrupt the smooth functioning of the plant. Once risk assessment has been completed, plans can be formulated to avoid those risks. Therefore, risk assessment indirectly contributes to the absorption phase of resilience. A deep insight into risk assessment and process safety was provided by O'Connor et al. (2019). They stated that there are three important factors that need to be considered from a safety perspective for any system, namely, prevention, mitigation, and response. These three factors together are referred to as safety triad. They proposed that these are the three factors that are solely responsible for process safety. Although these factors look intuitive and simple, investigation has revealed that most of the past disasters involved a lack of one or more of these three components. O'Connor et al. (2019) also stated that the idea behind resilience building is that hazard identification is never complete partly because a system continually changes with time; always some internal or also external hazard due to the technical or human factors is overlooked. Therefore, risk assessment plays a vital role for ensuring process safety. They defined risk assessment as a part of the Preventive aspect of the triad. According to them, decision making under uncertainty with the possibility of being confronted with unknown events is one of the biggest problems encountered during risk assessment. They promoted a systems thinking approach for tackling risk assessment. Following are some of the factors involved in a systems thinking approach:

- Understanding system structure:
  - Recognizing interconnections
  - Understanding and identifying feedbacks to the system
- Understanding dynamic behavior of the system:
  - Analyzing all the variables.
  - Understanding and identifying nonlinear relations.
- Reducing complexity of the system by modeling.
- Understanding the system at all different scales.

All the above-mentioned steps are interrelated and help in giving in depth and precise knowledge of the system under consideration, which in turn helps in risk assessment. O'Connor et al. (2019) also considered some socio-technical attributes of system resilience such as leadership, creativity, situation awareness and resources.

Minor fault sources tend to be overlooked while paying more attention towards the big picture scenario. Therefore, it is important to consider minor fault sources as well while proposing any resilience assessment methodology. Yoo et al. (2020) considered false alarms due to sensor faults while estimating resilience of a system. They utilized a probabilistic approach to measure resilience while accounting for sensor faults. Not much work has been done towards sensor fault consideration in resilience engineering, therefore the methodology proposed by Yoo et al. (2020) could be used towards resilient designing of sensors and alarms which are used frequently in chemical facilities.

As we have seen in some of the field studies earlier, human cognition plays a pivotal role towards resilience of a system. Some of the methodologies for resilience assessment used surveys or questionnaires for getting feedback from the workers to propose necessary changes in the system. Thus, it becomes necessary to ensure that the quality of feedback is not degraded due to lack of diligence from the survey takers. This criterion of getting quality feedback data is addressed efficiently by Patriarca et al. (2019). They explained the importance of leading safety indicators which provide feedback before an accident occurs. They illustrated how resilience based early warning methodology could be used for developing such leading safety indicators. The major challenge in this methodology is data gathering. Patriarca et al. (2019) described an alternative to conventional data gathering approach of tick box surveys and interviews. An alternative methodology for developing leading indicators using a gamified data gathering approach is presented. This methodology is used for setting up disaster situations in a gaming environment, in this way participation of the workers can be encouraged by getting rid of any psychological barriers and further enhancing the quality of the feedback data. Such alternative approaches towards data gathering could help in resilience assessment more effectively.

Another important aspect to be considered in resilience assessment methodologies is the possibility of multiple hazards. Some researchers have presented methodologies which do not consider the impact of multiple hazards or one hazard triggering another one (O'Connor et al., 2019; Yoo et al., 2020; Patriarca et al., 2019). A methodology of vulnerability assessment in the event of coupled multi hazard was proposed by Chen et al. (2019). Vulnerability is a characteristic of system which is observed when it is subjected to perturbations. Although vulnerability and resilience are different concepts, this methodology analyzes vulnerability from a resilience perspective. This type of methodology is important because resilience assessment considering the possibility of only a single hazard is inefficient, it is possible that one hazard could trigger another hazard and the resilience assessed earlier would no longer hold true. Also, Pescaroli et al. (2018) explored cascading events in a process system. The main goal of their work was to produce a replicable scenario-building process. This process could be used to set up a scenario of cascaded disaster such as fire accident in storage tanks for probabilistic resilience assessment in chemical plants.

Chemical plants consist of multiple process units which can be considered interdependent systems. The recovery phase of such interdependent systems will depend on the way restoration resources are being used. Restoration resources such as firefighting units are limited in nature and should be deployed after properly analyzing the disaster situation. If the restoration resources are used in a random way, then it could lead to more physical and economic losses. Also, time needed for recovery will increase drastically because of increased damages. Ouyang and Wang (2015) explored the restoration strategies of interdependent systems. They proposed that the efficiency of a restoration strategy will depend on variables like time to repair, sequence in which the individual systems are restored, and restoration resources. They used genetic algorithm to find the optimum sequence by minimizing the losses in a case study of hurricane incident. Hosseini et al. (2016) proposed another resilience assessment framework using Bayesian networks. Bayesian network is a popular tool used in many resilience assessment frameworks. It is used for measuring risks under uncertainty in a probabilistic way. It is used to depict dependencies between various factors that affect resilience.

The adaptive and absorptive phases of a chemical plant can be enhanced by implementing controllers. During the absorptive and adaptive phases, the controllers can maintain the process system output to its set value by their control action. Su et al. (2018) proposed a framework for resilience analysis of fault tolerant process control. The framework involved six steps: system identification, controller design and analysis (controllability, stability, resilience, etc.), hierarchical three-level control structures (model predictive control, state estimation, data reconciliation, etc.), risk mapping, assessment and planning strategies, and control performance evaluation. The key idea of this framework was to identify the potential risks associated with the control system design itself, and other process uncertainties, under which the control strategies will be evaluated. Como (2017) reviewed theories related to resilient control of dynamical flow networks such as transportation network, or a network of interdependent systems such as chemical plants. Lamnabhi-Lagarrigue et al. (2017) demonstrated that Systems & Control will be at the heart of most application domains in near future. Therefore, control applications should be investigated from a resilience perspective.

Matthews et al. (2014) analyzed how resilient design and hazard mitigation strategies are addressed within sustainability assessment frameworks. They demonstrated that hazard resistance and hazard mitigation are not prominently addressed in the intent of SAFs. Therefore, a future research area would be to inculcate resilient design in sustainability assessment frameworks of process systems. Dunn et al. (2017) reviewed research models addressing fire management. Although their review was specifically focused on wildfires, some of the aspects of fire management described in their review such as responder safety, job hazard rating, and fire containment standards like distance from fire perimeter for safety can also find applications in chemical plants where the probability of fire incidents is particularly high.

3.4. Mathematical modeling

Assessing resilience by mathematical modeling of the system has been a popular approach amongst researchers. Papers belonging to this category take a purely mathematical approach towards analyzing resilience in different ways. Utilizing fuzzy logic, probability and Bayesian network theory, optimization algorithms and mathematical modeling of hazards are some of the popular methods that have been used extensively in resilience assessment. Based upon how these methods are utilized, this category is further divided into three subcategories: Mathematical assessment frameworks, design optimization for resilience enhancement, proposing models for resilience enhancement.

3.4.1. Mathematical assessment frameworks

Mathematical assessment frameworks are like resilience assessment frameworks described earlier in sections 3.2 and 3.3. These frameworks utilize mathematical tools like graph theory, fuzzy logic, optimization algorithm, or statistical analysis tools like data envelopment analysis, principal component analysis and numerical taxonomy to estimate resilience. Resilience is quantified mathematically by defining certain numerical indices in some studies. These indices are system specific and they are generally referred to as resilience metrics. There are many factors that can be considered while defining a new metric, for example, socio-technical factors, flexibility, controllability, preparedness, and awareness depending on the system. Some papers in this category proposed innovative ways for resilience assessment and calculating resilience indices by using mathematical tools like fuzzy logic and Bayesian networks.

As discussed earlier, socio-technical factors play a key role in resilience of chemical plants. However, there is no accurate measure available for quantifying these factors. Surveys and questionnaires are some methods of estimating socio-technical factors for resilience assessment, but there is always a certain level of randomness in the data obtained from these methods. This is because the survey takers respond to the survey according to their individual mindset. Therefore, we can expect a spectrum of response data instead of a discrete response. It is necessary to address all these responses to ensure efficient resilience assessment. Therefore, researchers have been using fuzzy logic for in resilience assessment frameworks to address this randomness in survey responses. Fuzzy logic is a machine learning tool which usually used to model data with the uncertainty and randomness. For instance, fuzzy cognitive maps were used for resilience assessment by Azadeh et al. (2014a). These maps were used to calculate weights for factors which might affect the resilience of a petrochemical plant. Then a questionnaire was designed for a survey to verify the calculated weights. The weights calculated using the questionnaire and the fuzzy cognitive maps were compared. Both the questionnaire and the cognitive maps indicated the same set of factors as more important than the other factors. The results showed that awareness, preparedness, and flexibility are the most important factors from a resilience engineering perspective for a petrochemical plant. The most important attribute of this method is its unique way of data collection, instead of conventional survey questionnaires it uses fuzzy cognitive maps. A conventional survey can be conducted to find the most important factors affecting resilience and statistical tests can be used to check the reliability of the results (Jain et al., 2018a). However, fuzzy logic methods can address the data uncertainty and randomness more efficiently. Also, this method of resilience assessment could be easily extended to any other system, therefore it is not limited to petrochemical plants. Similarly, Aleksić et al. (2013) and Macuzić et al. (2016) proposed another framework using a fuzzy mathematical model for assessing and ranking the factors affecting resilience in process industries. The impact of socio-technical factors such as redundancy and teamwork on resilience were analyzed by Azadeh et al. (2016) using fuzzy mathematical programming. Azadeh et al. (2017c) also proposed a performance assessment from resilience engineering and lean production perspective, using a neural network method called multi-layer perceptron along with a fuzzy inference system. Azadeh et al. (2015a) analyzed the role and effect of resilience engineering in improving job satisfaction and occupational safety in laboratories. This study implemented an intelligent algorithm for assessing and improving job satisfaction by using questionnaires related to resilience engineering principles. The average result of the questionnaire is considered as input and job satisfaction as output for the proposed algorithm. An integrated neuro-fuzzy algorithm was used to find the most significant resilience factors that contributed to job satisfaction.

Data envelopment analysis (DEA) is another mathematical modeling tool that has been used frequently by researchers to model the effects of socio-technical factors in resilience assessment. DEA is generally used for performance measurement of systems which are impacted by many complex factors and when the exact mechanism of impact of those factors is unknown. This concept of DEA has been applied to resilience assessment where there are several managerial, technical, socio-technical factors, and resilience engineering principles which affect the resilience of process systems, but the exact mechanism of impact cannot be precisely determined. For instance, a questionnaire to identify the managerial shaping factors of resilience in a petrochemical plant was utilized by Azadeh et al. (2015b). First data was obtained through a questionnaire about the different factors that affect resilience of a process system already known from literature. Then DEA was performed to identify the most significant factors. Later, statistical tests such as sensitivity test and reliability test were performed to verify the results obtained. This was the common methodology followed by the studies which use DEA for resilience assessment. Zhao et al. (2018) implemented a hybrid approach by using fuzzy logic along with DEA for vulnerability and resilience assessment of chemical industries. Azadeh and Zarrin (2016) proposed a framework for productivity assessment of a petrochemical plant's working staff using resilience engineering principles and motivational factors by implementing DEA. Azadeh et al. (2014b) introduced a new concept of integrated resilience engineering which includes some additional resilience engineering principles: top-level commitment, reporting culture, learning, awareness, preparedness, flexibility, self-organization, teamwork, redundancy, and fault tolerant. This study evaluated performance of integrated resilience assessment approach in a petrochemical plant by analyzing the obtained data from questionnaires and DEA approach.

Principal component analysis and numerical taxonomy are some other mathematical modeling tools used for resilience assessment. The principal component analysis is a statistical technique used to examine the interrelations among a set of variables to identify the underlying structure of those variables (Shirali et al., 2016). Numerical taxonomy is the numerical evaluation of the affinities and similarities between variables. Numerical taxonomy helps in ranking those variables. Shirali et al. (2016) proposed a method for quantitative assessment of resilience safety culture of a petrochemical plant using principal components analysis and numerical taxonomy. Shirali et al. (2013) proposed another resilience assessment framework using questionnaire and principal component analysis. Six resilience indicators were chosen: top management commitment, just culture, learning culture, awareness and opacity, preparedness, and flexibility. The data obtained through questionnaire was analyzed based on principal component analysis and numerical taxonomy approach to quantify resilience of a process industry. More resilience indicators such as anticipation, monitoring, response, recovery, learning, and self-monitoring have been identified by researchers recently which can also be investigated using DEA, principal component analysis, and numerical taxonomy (Lundberg and Johansson 2015; Shi et al., 2018a; Srinivasan and Kumar 2015).

Time needed for recovery during the recovery phase plays a crucial role in restoration of a chemical plant to its normal working condition. Even though the probability of a multiple disasters occurring in a sequence in a short period of time seems to be low, the damage caused is exceedingly high. Therefore, it is important that the recovery time for a chemical plant or any other process industry should be minimized so that the damage caused due to the next disaster will not be as high as the damage caused by two back to back disasters occurring in a short period time and not allowing the chemical plant to recover. Argyroudis et al. (2020) proposed a framework for the quantitative resilience assessment of critical infrastructure, subjected to multiple hazards, considering the vulnerability of the infrastructure to individual hazard, and recovery time. The study identified a new resilience index, which accounts for the full, partial or no restoration of infrastructure damage between the subsequent hazard occurrences.

Economic implications of a disaster on a chemical plant are hardly addressed in the literature. During the recovery phase of a chemical plant, managers and operators focus on restoring the plant to its normal working conditions. But sometimes focusing too much on the recovery aspect alone can cause economic loss. For instance, if a chemical plant has been struck by a disaster and needs to be restored, then it can be either be restored gradually by reducing the production level and repairing the damages slowly over time, or it can be shut down completely and reparations can be carried out at a faster rate. The second choice can cause a higher economic loss as compared to the first choice because shutting down the plant completely will stop the production for a definite period. Also, shutting down and starting a plant is a tedious and time-consuming process. Hence, it is economically more beneficial to keep the plant running at lower production level and carrying out the reparations gradually. Therefore, recovery phase of a chemical plant can be modelled as an optimization problem where the economic loss is to be minimized and recovery should be maximized. The example presented above is too simple but, chemical plants are too complex and there are several factors that need to be considered while setting up this optimization problem. Gong and You (2018b) proposed a framework that identifies a set of disruptive events for a given system, and then formulates it as a multiobjective two-stage adaptive robust mixed-integer fractional programming model to optimize the resilience and economic objectives simultaneously. The model addresses equipment network configuration, equipment capacities, and capital costs in the first stage, and the number of available recovery processes and operating levels in each time period in the second stage.

Resilience assessment frameworks give a general idea about the resilience of a process system, but it would be more informative if the frameworks could give some idea about the three phases of resilience as well. This will illustrate the absorptive, adaptive, and restoration capacities of a process system. A framework for analyzing the level of adaptive capacity and identifying effective factors for developing adaptive capacity in the organizational structure of process industries was formulated by Salehi and Veitch (2020b). The data for this study was obtained through direct observation and a questionnaire survey. Data envelopment analysis was used to compute and analyze the role of the factors contributing towards adaptive capacity. Six features were used to measure and assess the level of adaptability during disruptions and upset events in process systems: management commitment, reporting culture, learning, awareness, preparedness, and flexibility. The results indicated that reporting safety issues played a central role in enhancing adaptive capacity. Management commitment and flexibility were also found to be vital factors in resilience enhancement. A similar study was performed by Salehi et al. (2020a) where the influence of teamwork and redundancy on adaptive capacity was analyzed using data envelopment analysis method. Multilayer perceptron (MLP), a machine learning approach, was used to estimate the adaptive capacity. Nonhomogeneous Hidden Markov Models (HMM) is another modeling technique used to evaluate adaptive capacity, absorptive capacity, and recovery capacity under different disruption scenarios (Zhao et al., 2016).

Resilient design of chemical plants is another area that has not been explored thoroughly in the literature. A resilient design would help in enhancing the absorptive capacity of a chemical plant and make it more resilient to disruptions. If the most vulnerable areas of a process system are identified, then appropriate measures can be taken to improve those areas. A method using past disaster data to predict upset event was formulated by Jain et al. (2018c). They used a machine learning approach by implementing a combination of Bayesian networks and deep learning to predict upset events in future using past disaster data. This method can be used in resilient design of chemical plants. By predicting the upsets, the related areas that can cause the upset can be analyzed to enhance the resilience of the plant. Ransolin et al. (2020) proposed a framework for identifying and analyzing the difference between environment as imagined in design and environment as done due to performance variations. They used functional resonance analysis method along with building information modeling for simulating the environment model. Then performance variations were analyzed based on the changes in the environment However, this study was related to health care units such as hospitals. But this idea of using FRAM for environment modeling can be also be used to simulate chemical plants for their resilience assessment.

3.4.2. *Design optimization for resilience enhancement*

Optimization is a powerful strategy that could be used to enhance resilience, but this area of research still appears to be relatively unexplored as compared to other research approaches. Optimization tools and principles could play a pivotal role in process system design. Process system design is closely related to the flexibility and controllability principles of resilience engineering (Dinh et al., 2012). A resilient system design could help in avoiding or surviving through a disaster by making the system more flexible to the disturbances and by improving its absorptive and adaptive capacity. A resilient design does not only refer to civil structures but also to the performance of the process system.

Optimization strategies for enhancing resilience of process systems have been explored recently by researchers (Cincotta et al., 2019; Jain et al., 2019a,b; Azadeh et al., 2017b; Salehi and Veitch, 2020a). Bayesian networks have been widely used in resilience assessment over the past six years. An optimal firefighting strategy for a system of inflammable tanks using Bayesian network in a process plant was proposed by Cincotta et al. (2019). They visualized the system of tanks as a Bayesian network and calculated the probability of combustion for each tank in the event of a fire hazard. Bayesian network is a mathematical modeling tool which considers uncertainty and variability while predicting the output of a model related to a complex system (Hossain et al., 2019). A Bayesian network consists of a set of nodes and edges where nodes represent variables and edges represent the relationship between the variables. It is basically a directed acyclic graph.

Fire hazards in chemical plants tend to trigger domino effects if the chemicals involved are flammable. It can be addressed using the resilient design approach. Cincotta et al. (2019) particularly addressed the 'domino effect', which in simple words implies the phenomena where one disaster leads to subsequent multiple disasters. This is a serious problem of multi hazards situation which needs to be investigated further from a resilience engineering perspective. They implemented a strategy that defined a function for calculating resilience using the performance function of the system. The performance function was defined using the probability of tank combustion. This resilience function was plotted and the area above the curve was used as a metric for estimating the loss in resilience. Now, different strategies of firefighting gave different resilience curves. Therefore, the strategy which gives out the least value for the area above the resilience curve is found to be the most resilient. This strategy can be used for chemical plants as well because storage tanks are frequently used in chemical plants.

A standard optimization method involves identifying the objective function that needs to be optimized and then identifying the variables that affect the objective function. Then variables can be adjusted to optimize the objective function. The objective function for chemical plants would be resilience and the variables can be socio-technical factors, economic factors, and safety measures. But design optimization of chemical plants has been rarely addressed in the literature. However, optimization strategies have been implemented for designing efficient maintenance strategies for chemical plant process units such as cooling towers (Jain et al., 2019b). They formulated a model for survival of a process system under upset conditions using a Process Resilience Analysis Framework. An objective function accounting for the overall system performance in terms of energy consumption, maintenance costs, safety impact, environmental impact, asset damage, and production loss was optimized to determine the optimal maintenance policy for resilient plant operations. Such objective function can also be determined for the resilience of chemical plant.

Resilient design also refers to resilience during an economic crisis. Resilience engineering principles can contribute to resilience against an economic disaster as well. A framework that emphasized on resilient operation design from an economic perspective was proposed by Azadel et al. (2017b). They investigated the performance of an aluminum plant during economic crisis. They concluded that resilience engineering principles such as self-organization, reporting culture, flexibility, and learning are conducive for resilience during an economic crisis. This framework followed the common methodology of mathematical assessment framework of using questionnaire to obtain data about the factors that affect resilience and then performing analysis using modeling tools like data envelopment analysis, principle component analysis and numerical taxonomy. Salehi and Veitch (2020a) performed similar analysis for performance optimization while considering job driven factors such as job stress, job satisfaction, job burnout, job pressure and reward along with resilience principles: top management commitment, reporting culture, learning, awareness, flexibility, and preparedness. It was concluded that job driven factors can also affect the resilience of a process system. This is a unique framework because it considers job driven factors that affect human performance. Effects of job driven factors on resilience and performance of process systems need to be investigated further along with other human factors.

3.4.3. *Proposing models for resilience enhancement*

Implementing mathematical models for resilience enhancement is another frequently used research approach after the mathematical assessment frameworks approach. This category of studies implements mathematical modeling tools like Bayesian networks, data envelopment analysis, principle component analysis, and machine learning approaches like neural networks to model the effects of disasters on process systems. This type of mathematical modeling can give a good estimate of the damage caused and it can also be helpful in designing a strategy for recovery and restoration. The difference between this category and mathematical assessment frameworks is that this category focuses not only on assessing system resilience but also on survival and restoration measures in the event of a disaster. These studies proposed purely mathematical models for resilience enhancement and span a variety of topics ranging from specific systems to broad areas like economic resilience and recovery. Studies in this category may overlap with the mathematical assessment frameworks category because some mathematical assessment frameworks consider survival and restoration measures too.

The resilience of systems whose physical properties and operation mechanisms are known, can be modelled directly without using any high-level modeling tools like data envelopment analysis. For instance, fragility, resilience, and recovery functions were proposed mathematically for cylindrical metallic tanks in industries located on coastal areas by Mebarki (2017). Resilience of these tanks in the event of a disaster like tsunami waves, floods or blasts was analyzed. The lateral pressure on the tanks is modelled mathematically using fluid dynamics and the loss in their bearing capacity is analyzed to derive a function for resilience.

On the other hand, if the exact operation mechanism of process systems is not known, then modeling techniques such as Bayesian networks (Hossain et al., 2019; Jain et al., 2019a; Tong et al., 2020; Abimbola and Khan 2019), mixed integer programming model (Gong and You, 2018a; Ribeiro and Barbosa-Póvoa 2018), fuzzy modeling (Azadeh et al., 2017a; Pasman 2015b), and functional resonance analysis method (Salehi et al., 2020b) can be used to model disaster impacts.

There had also been some attempts to use cognitive science tools for modeling resilient process systems (Sanz et al., 2014; Son et al., 2018). The use of such advanced modeling tools has been increasing since the last six years.

As seen in some of the earlier studies in mathematical assessment frameworks, Bayesian networks can be used to analyze and identify the most significant factors affecting the resilience of process systems (Jain et al., 2019a,b; Tong et al., 2020). For instance, Bayesian networks were used for resilience assessment and modeling of a deep-water port by Hossain et al. (2019). They used Bayesian networks to identify the most important factors that affect the port's resilience. Operation units in chemical facilities such as distillation columns, heat exchangers and reactors could be analyzed for their resilience by setting up a Bayesian network in a similar way. This strategy can be helpful in investigating the complex network of operation units in chemical facilities and identifying the key factors that affect the resilience of the facility. Different variations of Bayesian networks can be used to analyze absorptive, adaptive, and restoration capacities of process systems in real time. Abimbola and Khan (2019) used a dynamic object-oriented Bayesian network for resilience modeling. This method can be useful for comparing which capacity contributes the most to the resilience of a process system.

There are some unique mathematical modeling methods such as an input output linear programming model, mixed integer programming model and functional resonance analysis method which are used to model complex systems. The main advantage of these methods is that they do not require the exact operation mechanism of the system. Therefore, they are a perfect fit for modeling resilience effects on economic performance of process systems because the exact mechanism by which resilience engineering principles affect the economic performance of process systems is mostly unknown. For instance, an input output linear programming model for analyzing the energy-economic recovery resilience of an economy was proposed by He et al. (2017). They used models for energy production disruption, impacts on sectoral production and demands, and post-disruption recovery efforts in order to evaluate the minimum recovery investments needed to restore the economic production levels back to normal over a period of time. Ribeiro and Barbosa-Póvoa (2018) analyzed the resilience of supply chains using mixed integer linear programming. Gong and You (2018a) formulated a multi-objective two-stage adaptive robust mixed-integer fractional programming model to optimize the resilience and economic objectives simultaneously. Functional resonance analysis method is another popular method used for modeling and analyzing socio-technical systems (Salehi et al., 2020b).

Socio-technical factors have been an integral part of resilience of process systems. Surveys and questionnaires have been the only method used for analyzing these factors (Castillo-Borja et al., 2017; Pramoth et al., 2020). After obtaining data from the surveys, it is examined using data envelopment analysis, principal component analysis, fuzzy logic, and graph theory such as Bayesian networks (Azadeh et al., 2017a; Pasman 2015b; Shi et al., 2018b).

3.5. Summary of studies in industrial systems

All the field studies, case studies, methodologies and mathematical modeling studies are analyzed in Tables 1–4. After analyzing, four key research areas are identified which need to be addressed while investigating applications of resilience engineering principles in chemical facilities. They are: Multi-disaster situations; Socio-technical factors; Restoration strategies; Design optimization. Analysis of multi-disaster situations and socio-technical factors can help in formulating preventive measures to avoid disasters. Design optimization with respect to resilience can help in enhancing the absorptive capacity of a process system. Design optimization refers to optimizing the design with the goal of maximizing the resilience of the system. Restoration strategies are measures taken after the system has been hit by a disaster. They are crucial for the recovery phase of any process system. They are related to the administrative control principle of resilience engineering as proposed by Dinh et al. (2012). There are some inevitable disasters which cannot be prevented or detected earlier. Restoration strategies help in restoring the system back to normal working state. However, restoration strategies have not been explored to as much extent as preventive strategies. Restoring a chemical facility to its normal condition after being hit by a disaster could be an extremely difficult task because of the hazardous nature of the chemicals. It is important to address this research area in terms of a chemical facility. Multi-disaster situations occur when one disaster triggers another one. This successive progression of disasters is called as the 'domino effect'. Socio-technical factors such as unskilled work force can cause catastrophic incidents. As discussed in earlier sections, chemical facilities are highly susceptible to fire explosions and even minor human negligence can cause havoc. Therefore, it is necessary to address these factors during resilience assessment of chemical facilities as well. The following tables give a brief overview of work that has been done by researchers with respect to the four identified key research areas.

Table 1
Summary of some of the key research areas identified for papers belonging to the field studies category.

No.	Authors (year)	Identified research areas				
		Multi-disaster situation	Socio-technical factors	Restoration strategies	Design optimization	Others
1	Shirali et al. (2012)		x			Identifying challenges in building resilience engineering
2	Jain et al. (2018b)		x			
3	Dinh et al. (2012)		x	x		
4	Righi et al. (2015)					Systematic literature review
5	Shaw et al. (2014)		x			
6	Vidal et al. (2009)		x			
7	Li et al. (2019)					New risk assessment framework
8	Pasman et al. (2018)		x			Improved process hazard identification
9	Van Der Beek and Schraagen (2015)		x			
10	Nemeth and Herrera (2015)					Analysis of future of resilience engineering
11	Enjalbert and Vanderhaegen (2017)		x			
12	Okoh and Haugen (2015)					Explore robustness and resilience
13	Cabrera Aguilera et al. (2016)					Resilience of response system for oil spills
14	Pasman (2015b)		x			Accident analysis
15	Ehlen et al. (2014)					Chemical supply chain modeling
16	Asadzadeh et al. (2015)		x			Resilience indicators for disasters

Table 2
Summary of some of the key research areas identified for papers belonging to the case studies category.

No.	Authors (year)	Identified research areas				
		Multi-disaster situation	Socio-technical factors	Restoration strategies	Design optimization	Others
1	Lay et al. (2015)		x			
2	Mendonça and Wallace (2015)		x			Factors affecting organizational resilience
3	Labaka et al. (2015)		x	x		
4	Mebarki et al. (2014)				x	
5	Amodeo and Francis (2019)		x			
6	Saurin et al. (2014)		x			
7	Hu et al. (2015)					Fault propagation analysis from resilience perspective
8	Azadeh and Salehi (2014)		x			
9	Sonnemans and Körvers (2006)					Accident control mechanisms

Table 3
Summary of some of the key research areas identified for papers belonging to the methodologies category.

No.	Authors (year)	Identified research areas				
		Multi-disaster situation	Socio-technical factors	Restoration strategies	Design optimization	Others
1	Caputo et al. (2020)					Methodology for resilience estimation
2	Patriarca et al. (2019)		x			Data gathering through games
3	Jufri et al. (2019)					Resilience assessment of power grids
4	Yoo et al. (2020)					Resilience assessment in case of sensor faults
5	Chen et al. (2019)	x				
6	Ouyang and Wang (2015)					Resilience assessment of interdependent systems
7	Hosseini et al. (2016)					Resilience assessment using Bayesian networks
8	Su et al. (2018)			x		Fault tolerant process control design
9	Pescaroli et al. (2018)	x				
10	Matthews et al. (2014)					Resilience in sustainability assessment frameworks
11	O'Connor et al. (2019)		x	x	x	
12	Lamnabhi-Lagarrigue et al. (2017)		x			
13	Como (2017)					Resilient control of transportation networks
14	Dunn et al. (2017)			x		Framework for effective large fire response
15	Ranasinghe et al. (2020)		x			Review of resilience engineering indicators

4. Applications in ecological systems

These are the systems that involve environmental factors affecting a population. We reviewed how these factors affect the resiliency of these systems and what counter measures could be implemented. Natural disasters like earthquakes and tornadoes can have a deep impact on the entire community residing where the disaster takes place. To avoid these dreadful consequences, it is important to consider the fact that education is a key factor to the resiliency of the entire community (Campos 2020). Although the connection between education and resilience appears to be rather unclear, education about resilience can inculcate qualities like effective planning, order, and harmony. These qualities can develop an environment of physical and psychological wellbeing and a feeling of belonging amongst the community members (Campos 2020). Also, assessing health and safety management systems can boost the resiliency of a system right from the workers on the shop floor to the entire management (Costella et al., 2009). Observing the health and safety protocols is always an important factor in making a system resilient. Any anomaly detected by the health and safety management systems would indicate a possible disturbance in system operation, but if taken care immediately would make the system resilient to any plausible damages in future.

Supply of drinking water is crucial to the resiliency of ecological systems. Klise et al. (2017) demonstrated how the resiliency of drinking water resources can be improved using the software called Water Network Tool for Resilience (WNTR). This software simulated the effects of an earthquake on water distribution systems like underground pipelines. Simulators like these can be extremely helpful in recreating the effects of earthquakes on other natural resources as well. Water being an important resource for the survival of all kinds of life forms, makes it invaluable and therefore it becomes necessary to protect this resource in times of natural calamities. A framework approach lays down a set of rules and procedures to be followed to increase the resiliency of a system and Jafarinejad (2020) does the same. Jafarinejad (2020) illustrated the importance of wastewater treatment plants (WWTPs) and set up a framework for designing cost effective, energy efficient and resilient full scale WWTPs.

Along with natural disasters, climate is a major factor that impacts the resiliency of ecological systems (Beheshtian et al., 2018; Chen et al., 2018; Greenwalt et al., 2018). Beheshtian et al. (2018) performed a case study that explored how transportation energy systems in New York City are affected by climate change and introduced an infrastructure of alternative fuel as a synergistic approach to climate-adaptation and mitigation. Chen et al. (2018) took a different approach and developed a construction safety climate (SCR) model with resilience elements. SCR is measured by seven dimensions including management commitment, supervisor safety perception, co-worker safety perception, learning, reporting, anticipation, and awareness (Chen et al., 2018). The model

Table 4
Summary of some of the key research areas identified for papers belonging to the mathematical modeling category.

No.	Authors (year)	Identified research areas				
		Multi-disaster situation	Socio-technical factors	Restoration strategies	Design optimization	Others
1	Cincotta et al. (2019)	x		x		
2	Jain et al. (2019a)		x			Prediction and analysis of disasters
3	Marselle et al. (1982)				x	Resilient design of heat exchangers
4	Argyroudis et al. (2020)	x				Resilience assessment in multi-hazard environment
5	Jain et al. (2019b)		x		x	Data driven maintenance optimization
6	Jain et al. (2018a)		x			Use of resilience metrics for improved decision making
7	Azadeh et al. (2014a)		x			Resilience assessment using fuzzy cognitive maps
8	Mebarki (2017)				x	Resilience assessment of industrial tanks
9	Castillo-Borja et al. (2017)					Resilience index for process safety analysis
10	Aleksić et al. (2013)		x			Resilience assessment using fuzzy logic
11	Macuzić et al. (2016)		x			Assessment of organizational resilience
12	Azadeh et al. (2015b)		x			
13	Zhao et al. (2018)		x	x		Vulnerability assessment using fuzzy logic
14	Lundberg and Johansson (2015)					Systemic resilience model for contradictory resilience definitions
15	Reniers et al. (2014)					Resilience through attenuation-based security
16	Hossain et al. (2019)		x	x		Resilience assessment using Bayesian networks
17	Wang et al. (2019)					Modeling of energy infrastructures from resilience perspective
18	Azadeh et al. (2016)		x			
19	Azadeh et al. (2017b)				x	Performance optimization during economic crisis
20	Gong and You (2018a)				x	
21	Fraccascia et al. (2017)		x			Resilience in industrial symbiosis
22	He et al. (2017)					Economic resilience
23	Govindan and Al-Ansari (2019)					Resilience enhancement of food, energy and water nexus
24	Ribeiro and Barbosa-Póvoa (2018)					Supply chain resilience
25	Azadeh et al. (2017)				x	
26	Azadeh and Zarrin (2016)		x			
27	Azadeh et al. (2017c)				x	
28	Srinivasan and Kumar (2015)					Resilience of dynamic systems subjected to disturbances
29	Shi et al. (2018a)					Review of resilience theories
30	Pasman (2015a)					Summary of different resilience analysis tools
31	Shi et al. (2018b)					Resilience assessment using graph theory
32	Gong and You (2018b)				x	
33	Sanz et al. (2014)		x			Resilience enhancement using controllers
34	Son et al. (2018)		x			Modeling an incident management team
35	Tong et al. (2020)		x			Resilience assessment using Bayesian networks
36	Holt and Morari (1985)				x	
37	Zhao et al. (2016)		x			Resilience analysis and metric using hidden Markov models
38	Salehi et al. (2020b)		x			
39	Pramoth et al. (2020)		x		x	
40	Salehi and Veitch (2020b)		x		x	Analysis of adaptive capacity of petrochemical plants
41	Salehi et al. (2020a)		x		x	Analysis of adaptive capacity of petrochemical plants using Machine Learning
42	Li et al. (2020)				x	Loss estimation using Stochastic modeling
43	Ransolin et al. (2020)				x	Resilient design using FRAM and BIM
44	Salehi and Veitch (2020a)		x		x	Performance optimization of workers in ceramic tile company using DEA
45	Abimbola and Khan (2019)		x			Absorptive, adaptive, and restorative capacities modelled using Bayesian networks
46	Jain et al. (2018c)		x			Upset event prediction using Bayesian deep learning
47	Shirali et al. (2016)		x			Resilience assessment framework
48	Azadeh et al. (2015a)		x			Algorithm for job satisfaction assessment
49	Azadeh et al. (2014b)		x			Resilience assessment framework
50	Shirali et al. (2013)		x			Resilience assessment framework

was validated by taking surveys from different construction sites. Climate change is also a result of ever-increasing urbanization. Cities have been a major source of greenhouse gases responsible for global warming and in turn climate change (Greenwalt et al., 2018). This makes it extremely important for us to switch to proper urban planning which would not only make the cities more environmentally friendly but also more resilient. Additional steps like resorting to more efficient energy resources will also help in making the urban areas less susceptible to disasters.

5. Applications in interlinked systems

Interlinked systems comprise a complex network of interconnected systems which function simultaneously. The exact mechanism by which these systems affect each other may or may not be known. Examples of these systems can include financial systems such as the stock market or supply chains. Most of the time, these systems tend to be unpredictable such as the supply chains of an industry. Natural disasters such as earthquakes or tsunamis can obstruct a company's supply to the affected area. This can adversely affect the financial condition of that company.

Similarly, accidents at process plants could be harmful to the company's profit. Also, unpredictable changes in the stock market could damage the company financially. Chemical industry is equally susceptible to such financial crises. Many chemical companies manufacture specialty chemicals which are used as raw materials by other chemical companies. So even if one of them fails to manufacture, then it might disturb the whole chemical industry. Therefore, it becomes important to protect such complex systems by enhancing their resilience to such disasters. As shown in Fig. 6, resilience of interlinked systems has gained popularity in recent years. This research area could be explored more in near future because it is relatively new. Pashapour et al. (2019) introduced a qualitative and quantitative framework for economic resilience for the first time. They demonstrated the use of its framework by applying it to a petrochemical plant. They also proposed a questionnaire which was used to identify the most important factors affecting economic resilience of the plant. Such framework can also be implemented for chemical plants.

Resilience enhancement of interlinked systems involves more managerial aspects rather than engineering aspects. For instance, Duijnhoven and Neef (2014) explained how resilience enhancement could be achieved from a managerial approach. They demonstrated why a shift from a model-based approach to a management approach is essential for resilience against economic crises.

6. Results and discussion

Figs. 6 and 7 illustrate the number of papers along with their respective percentages in three categories of systems. They suggest that the application of resilience engineering in industrial systems has been the primary focus of research related to resilience engineering from 2015 to 2020. There has been an increasing focus on applying resilience engineering principles to industrial systems to make them resilient to future disasters. For instance, Parker et al. (2019) used the safety triad concept proposed by late Dr. Mannan to investigate the toxic chemical release accident at the DuPont La Porte facility. Later, Parker et al. (2019) proposed strategies that could be used to reduce the likelihood of such incidents in the future. Fig. 6 suggests that there has been an increase in research related to resilience engineering application in ecological systems since 2017. This could be a result of the increasing occurrences of natural disasters causing a disruption in ecological systems like a community of people, wildlife, and climate. Awareness amongst the researchers about environmental problems that cause natural disasters has provided an impetus to the research associated with application of resilience engineering.

We analyzed the papers in all the four sub-categories of industrial systems applications from 2015 to 2020. This helped in identifying the key research areas more efficiently. Amongst these sub-categories, there was no trend that could be observed since 2015. However, there has been an increase in the proportion of papers dealing with methodologies for resilience, as shown in Fig. 8. Also, it can be observed that mathematical modeling has played a significant role in the research on the resilience engineering applications as shown in Fig. 9. Mathematical modeling approach has been the most preferred approach for all years since 2015. It seems to be an evolving research area because of the advancement in computational technologies and increasing attempts to make process industries automated.

As shown in Fig. 10, for applications of mathematical modeling in resilience engineering, it was observed that exploring mathematical assessment frameworks has been the major focus for the past six years. This trend is also observed for field studies, case studies and methodologies, where investigating new resilience assessment frameworks have a significant contribution to the literature. However, in the case of mathematical modeling category, proposing mathematical models for resilience enhancement has been another significant contributor to the literature as it is evident from Fig. 11. The research area of application of optimization principles for resilient design remains comparatively unexplored.

After reviewing the studies related to industrial systems it is clear that the research in resilience of process industries is heavily focused on analyzing the effects of socio-technical factors. This is because of the inherent nature of the concept of resilience which deals with human factors. This inherent nature of resilience is also the reason for large number of applications of resilience in fields like health care industry, cognitive sciences, urban planning, etc. As all these fields are heavily dependent on human interactions, resilience research is more developed for these fields as compared to engineering fields.

However, the research related to resilience assessment of process industries has been garnering more attention from scientific community. This is because of the frequent occurrence of disaster incidents in process industries. While addressing the resilience of process industries, it is particularly important to analyze the factors affecting resilience quantitatively as well as qualitatively. This is because we need concrete evidence for formulating disaster recovery policies. Therefore, qualitative data alone is insufficient. This why we observe that majority of studies related to resilience of industrial systems are focused on mathematical modeling. Mathematical modeling techniques, as we had described in

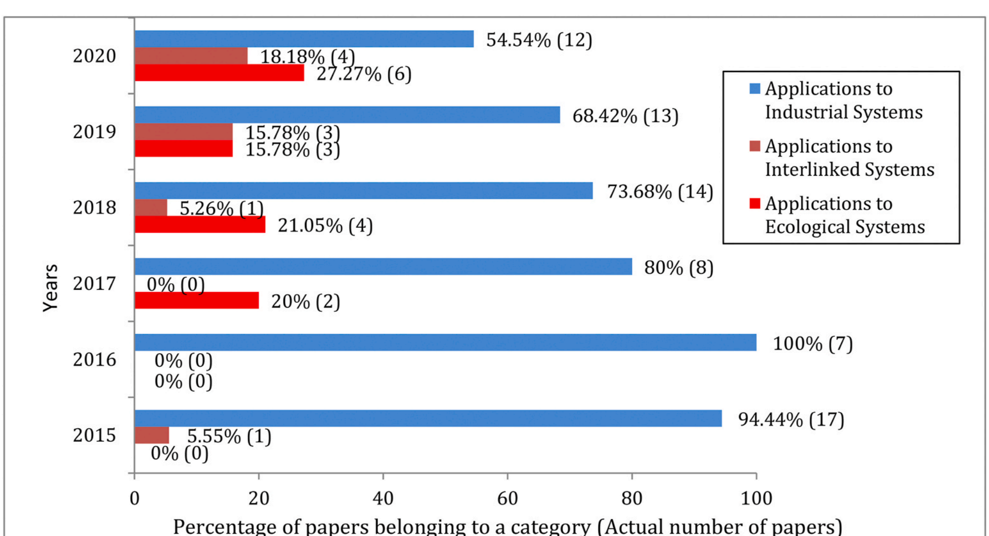

Fig. 6. Histogram for the percentage of papers published in all the three categories (2015–2020).

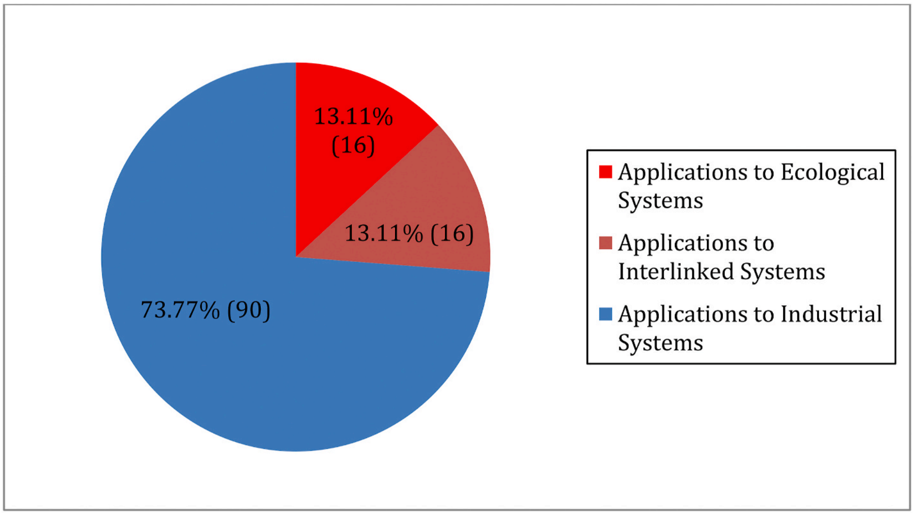

Fig. 7. Pie chart displaying the proportion of all the three categories out of the 122 selected for review.

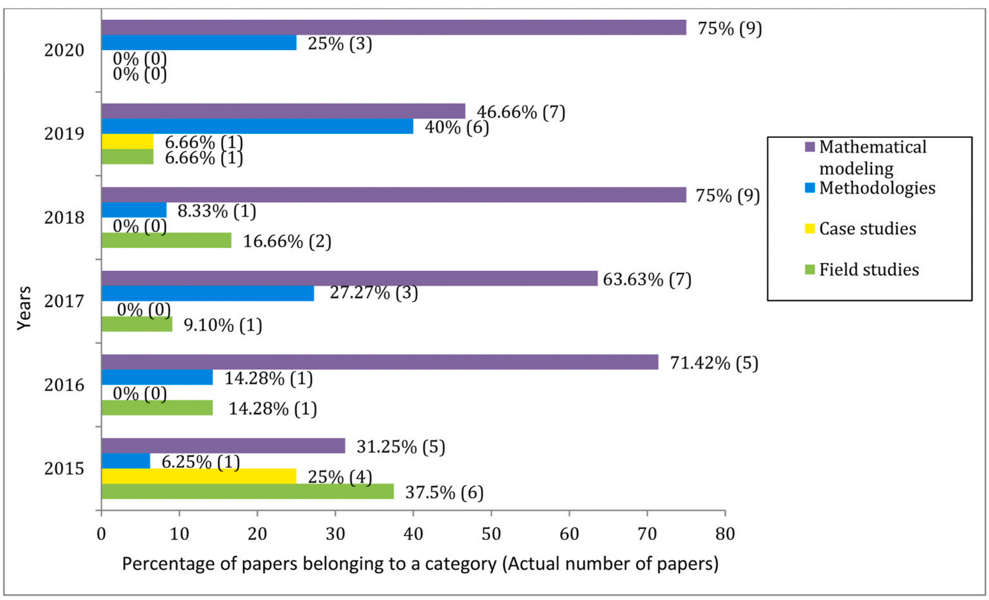

Fig. 8. Histogram for percentage of papers published in all the four categories each year.

the earlier sections, are instrumental in analyzing the effects of various factors on resilience of a process system.

The concept of a resilient design has not been adequately explored in the literature. This concept is not just limited to physical performance, but it can be extended to economic performance of a process industry. Resilience engineering principles like flexibility, controllability, and human factors such as job stress, job pressure, and fatigue also affect the economic performance. Therefore, it is important to carefully consider all the factors that affect resilience as well as economic performance while formulating a disaster recovery plan. This can be achieved by using surveys and questionnaires related to the resilience engineering factors. The data obtained can then be modelled using mathematical tools like data envelopment analysis, fuzzy logic, principal component analysis and numerical taxonomy to identify the most significant factors and then address them accordingly. This is the standard methodology followed by resilience assessment frameworks.

There have been some other review papers related to resilience engineering in the past (Bergström et al., 2015; Patriarca et al., 2018; Ranasinghe et al., 2020) but they did not review the literature from the perspective of resilience of chemical plants. Ranasinghe et al. (2020) explored the resilience indicators that have been identified so far in the literature across 11 high risk industries. Whereas Patriarca et al. (2018) explored the studies on resilience across different fields such as engineering, social sciences, computer science, medicine, chemical engineering, business, management and accounting, environmental science, and decision sciences. These reviews on resilience only identified the most prominent research areas. Our study identifies some key research areas in resilience engineering as well as the approaches that have been taken to investigate those research areas. We employ a classification method based on the type of system under consideration and the approach taken by researchers for investigation. Therefore, our study will help the readers to learn about the key research areas in resilience engineering as well as the different approaches and techniques being used in resilience research. It will help the researchers to focus on the key research area of their choice and give them a guideline for approaching that area based on past studies.

For researchers who work with high risk and high impact process systems like chemical plants, this review implies that resilience

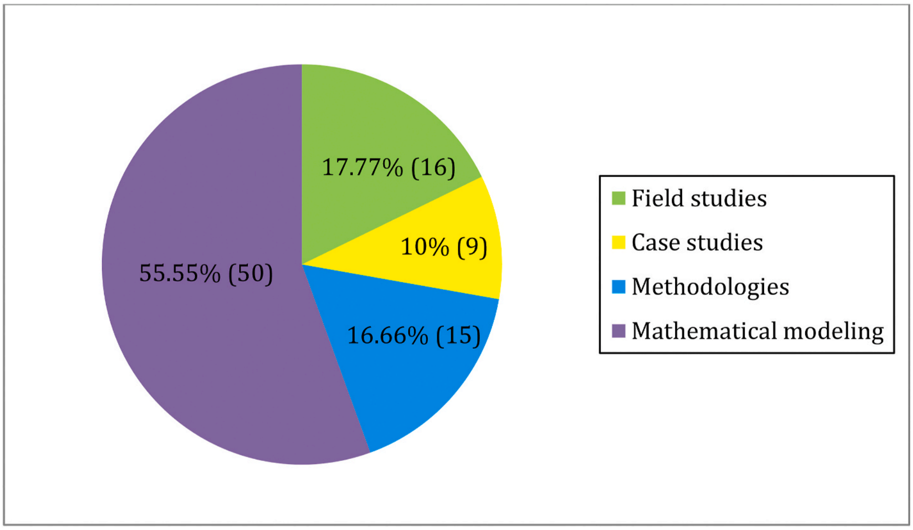

Fig. 9. Pie chart displaying the proportion of all the four categories out of the industrial systems application category.

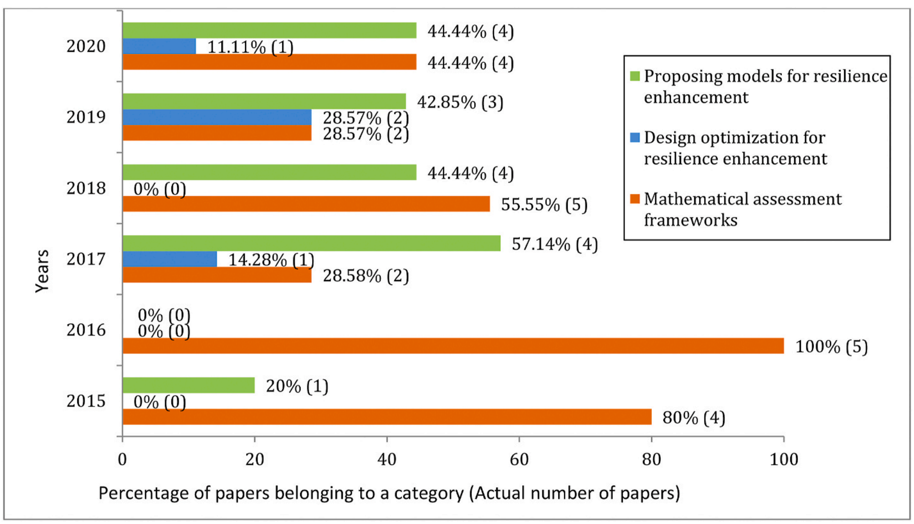

Fig. 10. Histogram for percentage of papers published in all the three categories each year.

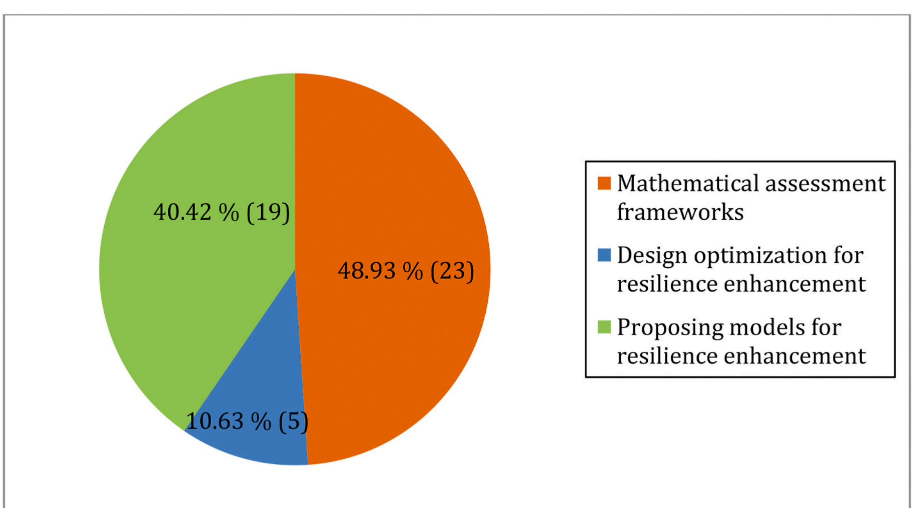

Fig. 11. Pie chart displaying the proportion of all the three categories out of the Mathematical modeling category.

engineering principles should be considered while addressing the safety of the system. Usually disasters caused due to human errors are not addressed as extensively as the Na-Tech incidents. Therefore, these principles are often neglected because they are related to human factors. However, these principles can be analyzed and their effects on resilience can be modelled using the methods described in this review.

7. Limitations and future research directions

Although this study used a classification-based approach for identifying the key research areas in resilience engineering applications to chemical plants, it has some limitations. First, the classification of the literature reviewed in this study was exclusive. Although more than one category was overlapped in several research papers, these papers were exclusively categorized into only one category. Second, it is possible that some relevant papers were neglected, and some less relevant paper were included in this review. This is because the criteria used for selecting relevant research papers for this review were broad. Third, while searching for studies to review, only the studies in English were considered. Studies in other languages would have added more valuable information. Fourth, the ScienceDirect and Web of Science databases provided relevant articles for review, but some other relevant articles from other databases might have been ignored.

Future work could be based on strategies such as fuzzy logic and advanced data-gathering tools which were discussed earlier in the literature. A new data gathering tool will help in coping with the unreliability issue of data obtained through surveys. After data collection, recently developed machine learning and deep learning techniques could be integrated into resilience engineering as well as any safety related research (Jiao et al., 2020). Domino effect and consequence analysis need to be considered more extensively in resilience assessment frameworks for chemical plants maybe coupling with CFD modeling (Shen et al., 2020). The economic performance of chemical plants should be addressed along with resilience using machine learning tools in the future. Investigating efficient restoration strategies for resilience enhancement could be another promising research area to look forward to in future.

8. Conclusions

After reviewing the literature, we concluded that research in applications of resilience engineering principles to industrial systems was focused in four major areas: effects of socio-technical factors, multi-disaster situations, design optimization, and restoration strategies. A major emphasis on resilience estimation through field studies, case studies, methodologies and mathematical modeling was observed. Therefore, we concluded that there is an increasing focus on quantifying resilience using different strategies. For example, more efficient assessment frameworks are being developed with the help of advanced data gathering methods such as fuzzy logic, resilience metrics and indices, instead of conventional pen and paper surveys.

This study identified that consideration of socio-technical factors in resilience assessment has been another popular research topic. About 52% (47 out of 90) of the studies in the industrial systems category were found to be related to the effects of socio-technical factors on resilience. There have been several new strategies proposed in the literature for modeling the socio-technical factors and investigating how they affect resilience in industrial systems. New methods such as fuzzy cognitive maps and gamified data collection have been proposed in the past as an alternative to conventional survey questionnaires for analyzing socio-technical factors. This could be a prominent research area because human factors play a major role in industrial operations and even slight negligence can lead to catastrophic results. There have been multiple instances of human negligence leading to chemical plant disasters and hence, this area is important even from a chemical engineering perspective. We reviewed some studies which implemented machine learning techniques for analyzing these factors. Therefore, we can expect to see some major breakthroughs in this research area because of the advancements in machine learning and artificial intelligence technologies.

Besides, there was an increase in the literature that addresses the issue of successive events within one disaster. Although there was not much literature available about this particular issue, it would be an important research area that needs immediate attention because there have been incidents in the past where one disaster triggered another one leading to catastrophic effects. This phenomenon is usually referred to as the “domino effect”. There have been some studies done earlier that considered the possibility of multiple disasters in the resilience assessment frameworks. However, they only accounted for about 4% (4 out of 90) of the studies in the industrial systems category.

This study also figured out that design optimization is a new research area that needs to be addressed in the mathematical modeling research. Only 18% (17 out of 90) of the studies in industrial systems category addressed design optimization. This area of research remains vastly unexplored because most of the literature focuses on estimating the resilience of an established industrial system and then suggesting measures for enhancing resilience. This strategy is more like a remedial measure but if resilience engineering principles are considered while designing the system in the initial phase, then it would make the system safer and more resilient.

Finally, the findings of the study indicated that most of the literature focuses on disaster avoidance and survival aspects of resilience. Restoration plays a key role in bringing the system back to its normal operating condition once a disaster strikes. Only 8% (8 out of 90) of the industrial systems studies addressed restoration strategies from resilience engineering perspective. Therefore, it should be investigated further.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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