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Development of an industrially applicable model for the qualitative resilience assessment of process systems at the early design stage

Freya Vesey^{a,b}, Seyed Mojtaba Hoseyni^a, Joan Cordiner^{a,*}

^a Department of Chemical and Biological Engineering, The University of Sheffield, Sir Robert Hadfield Building, Mappin Street, S1 3JD, Sheffield, UK

^b Cavendish Nuclear, 106 Dalton Ave, Birchwood, Risley, Warrington, WA3 6YD, UK

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ABSTRACT

Traditional design methodologies do not effectively extend to consider a resilient system capable of absorbing disruptions and recovering from their consequences. This highlights the need for a practical resilience analysis model which can be used at the design stage. While the concept of resilience is widely discussed, there is currently no agreed-upon methodology to quantify it. From a review of existing works, this paper presents a specific definition of resilience as a process safety concept. A novel model for assessing and scaling process system resilience during the early design stage is proposed in line with this definition. The proposed methodology entails a standardized analysis for measuring and comparing resilience, allowing for the simplified and accessible analysis of resilience across industry. The model combines analyses of resilient design by an index-based quantification, vulnerability to high-impact unexpected events (beyond design basis events), and assesses the potential for severe impacts due to such events. The model facilitates cost-benefit assessments for design improvements towards resilience and presents an effective tool for introducing resilience as a design concept.

1. Introduction

Resilience is a crucial component of engineering and refers to a system's capacity to adjust, recover, and continue functioning upon impact by unanticipated or unfavourable circumstances; a valuable concept for considering severe and low likelihood Beyond Design Basis Events (BDBEs) (Hollnagel, et al., 2008). Engineering systems, processes, and structures should be tested to assess their ability to endure all severe events as a resilient system will be less susceptible to catastrophic failures and have reduced consequences when impacted by a BDBE; including impacts to human casualties, property damage, and environmental catastrophes (Provan, et al., 2020).

Process safety resilience is a relatively new concept for the consideration of BDBEs that has received a lot of attention in recent years (Pasman, et al., 2020). The goal of a traditional hazard analysis is to lower the risk of a hazard having an influence on a process system by studying risk as a function of hazard occurrence probability and consequence (Pourgol-Mohammad, et al., 2016; Yousefpour et al., 2017; Hoseyni et al., 2014). Alternatively, resilience in the process safety context describes the ability of a system to tolerate interruption, prevent catastrophic failure, and recover from the disruption. The concept of

resilience involves conducting a deterministic analysis of how a system would respond to the impact of an event (Hollnagel, 2013). The analysis considers various scenarios and aims to determine how a system would cope in each case. This is an important concept to examine when considering extreme and unforeseen events such as natural catastrophes and terrorist attacks, that due to their low probability would not be sufficiently accounted for using conventional hazard analysis studies (Righi, et al., 2015). As the impacts of climate change cause more severe and frequent environmental disasters, the prospect of new pandemics looming over societies, and global political unrest suggests a pursuing terrorism threat, it is becoming appreciated that severe BDBEs must be considered, despite their low likelihood. This describes that these events are expected to continue (or worsen in the case of environmental disasters) and therefore a sole reliance on conventional risk and resilience analysis should no longer be seen as sufficient.

Process safety resilience is in its early stages of development, with no universally agreed upon definition beyond its general concept, and no widely accepted framework for its measurement (Demichela, et al., 2015). As a result, resilience is often implemented insufficiently due to a lack of practical understanding of the term, a focus on cost saving, and a tendency for normalcy bias (Shirali, et al., 2012). To promote the

* Corresponding author.

E-mail address: j.cordiner@sheffield.ac.uk (J. Cordiner).

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widespread understanding and adoption of resilience as a critical concept in industry, there is a need for a standardized, accessible, and broadly applicable model for its quantification (Yarveisy, et al., 2020). Such a framework should be relevant to and easily applicable across various process sectors.

Regardless of the advantages of earlier research efforts, a review of current models for assessing resilience reveals that many rely on detailed dynamic simulations of system responses to discrete disruptions, which can be impractical to complete during the design stages and require significant assumptions to be made (Kang, et al., 2017). These methods are complex and require a high level of safety understanding and sophisticated discrete accident scenario modelling, making existing methodologies inaccessible and impractical for many organizations (Chen, et al., 2023). Furthermore, simulating all possible hazard scenarios is not feasible, and existing quantification approaches do not provide insights into how system characteristics contribute to resilience. As a result, an industrial driven methodology that provides a practical view of resilience and identifies the design consequences of resilience improvements is required for organizations to act upon.

This paper aims to present a novel approach for qualitative resilience assessment that is both simple and clear, allowing for easy comparison between systems and adoption throughout the process industry; crucially needed to offer a standardised assessment technique that simplifies the methods for assessing process resilience. Furthermore, the creation of an accessible assessment methodology encourages the widespread adoption of the chosen resilience definition, aiming to align thinking across industry. This is further necessary as there are high rates of retirement across all sectors, leading to a loss of expertise. Additionally, with the added strain of the Covid-19 pandemic and global competition, some organizations may be tempted to cut back on investments in areas such as process system resilience (Parliament, 2021; Castillo-Borja, et al., 2017).

The purpose of this paper is to establish a definition of resilience and identify the engineering qualities that promote it. This definition will be used to create a user-friendly and uncomplicated model for measuring resilience. The model is prepared for the process industry but is applicable in various industries, capable of assessing resilience during the early design phase to ensure it becomes a fundamental design principle. The aim is to simplify the concept of resilience and encourage its widespread adoption as a safety analysis tool. The research will also improve our understanding of resilience and pave the way for further advancements in the field.

To better understand resilience, a novel non-probabilistic worst-case scenario model is presented that defines the resilience of a system as the combination of three main pillars of system properties: 1) resilient design, 2) potential impacts, and 3) vulnerability. Resilient design evaluates how effectively an engineering system can respond to disruption by the survivability and recoverability characteristics of the design. Potential impact evaluates the adverse impacts that disruptions can impose on the economy, environment, and human health. Finally, the vulnerability of the system to BDBEs describes the extent of resilience consideration required for a system. The combination of these three attributes provides a novel evaluation of the factors contributing to an engineering system's overall resilience to BDBEs. The application of the model is shown in the resilience assessment of an ammonia and urea production process located in the US and a p-aminophenol production plant located in India. Design modifications that can improve the system resilience and a cost-benefit analysis is discussed for the case studies.

The remainder of this paper is organized as follows: Section 2 introduces the novel model for qualitative resilience assessment at the early design stage. Section 3 provides two case studies to demonstrate the application of the model and the discussion of the results of the resilience assessment and cost-benefit analysis. Section 4 ends the paper with concluding remarks.

2. Proposed resilience model

A new model has been developed to provide a practical and accessible methodology for measuring resilience in engineering settings; critically needed to encourage the widespread understanding and application of resilience in industry. The proposed approach includes the following features:

- Avoiding the use of complex system modelling
- Providing a single, comprehensive measure of a process system's resilience to a range of potential BDBEs
- Identifying the system properties that affect resilience, thereby pointing to strategies for resilience improvement

The proposed methodology for measuring resilience can evaluate the potential impacts of a BDBE on human health, economy, and the environment. It aims to assess a wide range of possible BDBEs and is designed to be simple and easily conducted by industrial organizations.

To tackle the above mentioned concerns, the resilience of a system is assumed to be related to, firstly, the design of a system and the arrangements considered to make a resilient system, called 'Resilient Design' hereafter. The model is designed to be used for systems with the potential for extremely severe hazards, and it includes the factors 'Potential Impact' and 'Vulnerability' to analyse the necessity for investment in additional resilience features of the design. The potential impact analysis assesses the scale of consequences due to severe and unexpected hazards, while the vulnerability analysis describes a system's risk of suffering serious consequences to an initial hazard and falling victim to severe impact, taking into consideration the ability for the propagation of impact through a system. The resilience Ψ , as shown in Equation (1) is defined as a combination of these three system attributes:

$$\Psi = \frac{D}{I \times V} \quad (1)$$

where D represents resilient design, I represents potential impact and V represents vulnerability.

The evaluation should be employed as a means to determine resilience from the initial stages of design and continued throughout the process as new information becomes available and factors of resilience become more applicable. This approach will guarantee that resilience is always an essential design principle during the system's development and that investments made towards enhancing resilience are reasonable and worthwhile.

Fig. 1 shows the schematic presentation of the proposed model for resilience assessment at the early design stage that relates the resilience to the three main attributes of D , I and V . Detailed discussion on each attribute is provided in the following sections.

The model is designed for iterative use to assess and improve system resilience. This involves calculating initial system resilience and then simulating the system again with improvements until an economically favourable design with adequate resilience is reached. The foundation of the introduced approach lies in the innovative breakdown of resilience into three distinct factors, a concept not previously explored in existing literature. Resilience, defined as a system's elastic capacity to survive the accidents disruptions and recover from their consequences, underscores the pivotal role of resilient design (D) and vulnerability (V) in withstanding disruptions and facilitating recovery, particularly in the pre-accident phase. In contrast, the factor of potential impact (I) sheds light on system characteristics related to resilience in the post-accident phase. The complex interaction of these three variables provides a thorough picture of a system's resilience over the course of its lifecycle, from proactive design aspects to its flexibility and adaptability in the face of unfavourable occurrences and the subsequent recovery process in the post-accident phase.

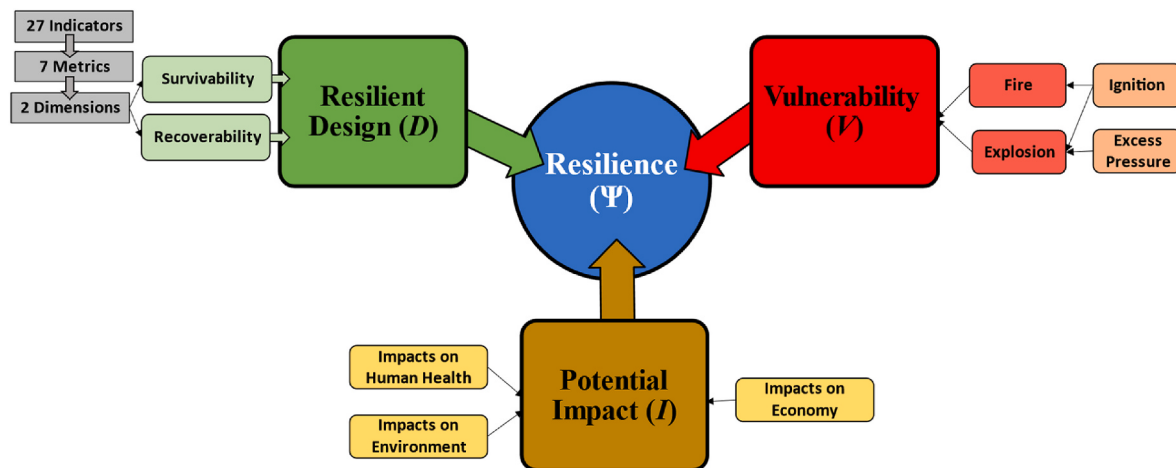


Fig. 1. Schematic presentation of the proposed model for resilience assessment at the early design stage.

2.1. Resilient design (D)

Resilient design is the process of creating an engineering system that can survive shocks and stresses and then recover in a timely manner. This can be achieved by defining the attributes of the resilient design at the early design stage and evaluating their qualities by expert judgment. This allows for clear comprehension and quantification of the properties that make a system design resilient and will transform resilience into a measurable concept, allowing for its analysis, comparison between systems, and measurable improvement. Attributes are posed to allow for issue identification and to stimulate effective resilience-based discussion within a design team and should be answered with collaborative input from all relevant technical staff (Øien, et al., 2010).

The response of a system to a disruption entails two major attributes of the system to survive the disruption and then recover to its normal performance level (Poulin and Kane, 2021) as shown in the resilience curves of Fig. 2 where three typical resilience curves with a) full recovery, b) partial recovery, and c) total collapse of the system after the disruption are shown.

As can be seen in Fig. 2, a system must first survive a disruption by

minimizing the negative effects of a disruption on the performance level (point 1 to 2 in curves a and b) and then must recover to partial (point 2 to 3 in curve a), or full performance prior to impact (point 2 to 4 in curve b). With no survival and recovery, the performance level falls immediately and the system collapses with no recovery (curve c). To quantify resilience, the attributes of resilient design must first be clearly defined. As resilience describes a process system's ability to both survive significant disruption with minimal consequences and then recover to normal performance level, the concept is seen to be a function of two distinct attributes or dimensions of resilience; 'survivability' and 'recoverability' as described below (Yodo and Wang, 2016):

- **Survivability:** Survivability captures an engineering system's ability to minimize the severity of impact due to a disruption (Taleb-Berrouane and Khan, 2019).
- **Recoverability:** Recoverability captures an engineering system's ability to undergo corrective actions to recover from a disrupted operation (El-Halwagi, et al., 2020).

To evaluate the specific system dimensions of survivability and

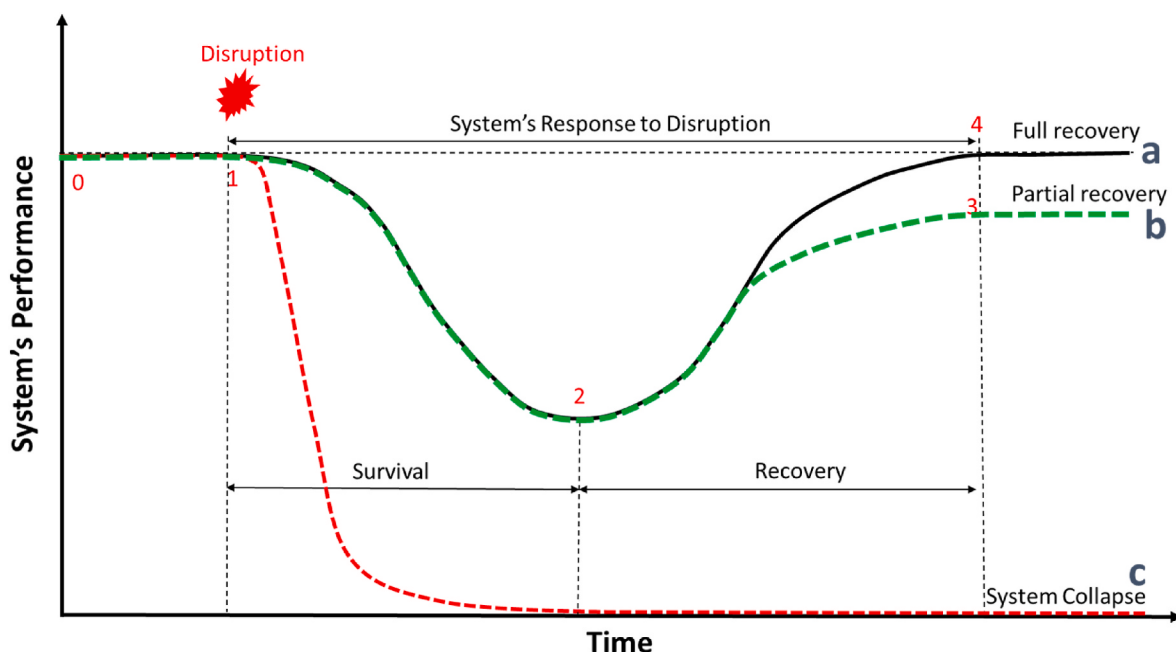


Fig. 2. Three resilience curves for: (a) full recovery, (b) partial recovery, and (c) system collapse.

recoverability other detailed attributes of the system design referred to as metrics of resilience are defined. A collection of metrics will be used to describe each dimension, effectively capturing the many elements which contribute to resilience. Many metrics exist in literature which have been reviewed and the necessary collection to effectively describe resilience have been presented below:

Metrics of the Dimension of Survivability:

- **Early Warning:** The ability of the system to detect anomalies early by condition monitoring and proper alarming for disruptions (Dinh, et al., 2012).
- **Robustness:** Robustness denotes the given level of stress that a system can withstand without consequences to performance (Bruneau and Reinhorn, 2007).
- **Absorptive Capacity:** Absorptive capacity describes the portion of the impact of a given disruption that the system can neutralise or absorb (Francis and Bekera, 2014).
- **Flexibility:** Flexibility describes a system's ability to acceptably operate over a wide range of process conditions due to error-tolerant design (Dimitriadis and Pistikopoulos, 1995). The term can also be seen as the dampening ability of a process to operate normally, maintaining performance, despite disruption (Dinh, et al., 2012).

Metrics of the Dimension of Recoverability:

- **Resourcefulness:** A system's level of recoverability depends on the available resources and the ability to mobilise them to quickly recover from the consequences of disruption (Yodo and Wang, 2016).
- **Controllability:** Controllability describes the ability to direct and steer a system from a dynamic and disrupted state to a recovered equilibrium state (El-Halwagi, et al., 2020).
- **Reconfigurability:** Supporting resourcefulness, reconfigurability describes the ability of a system to smoothly transition to and operate

with different configurations to reinstate safe operation (Sheffi and Rice, 2005).

Each metric should be described and quantified based on specific and measurable system properties, indicators of resilient design (Munoz and Dunbar, 2015; Huber et al., 2012). In this work, we define 27 indicators of resilient design based on technical and administrative factors that take engineering design as well as human factors into account. Fig. 3 depicts the schematic presentation of the proposed model for the resilient design that defines the resilience as the attributes of dimensions, metrics and indicators.

These indicators are developed with the philosophy of broad applicability to ensure the model is relevant to a wide variety of process systems. Furthermore, each indicator gives an independent pathway to improved resilience meaning any combination can be altered to give a flexible strategy for improvement. It should be noted that the presented collection of indicators can be seen as a starting point to evaluate the system response to disruptions at the early design stage. The presented indicators reflect the understanding of resilience at the time of writing, and review of indicators may be necessary in future revisions of the model as the practical implications of resilience is further explored and understood across industry and academia.

Each indicator (i) is evaluated with a quantitative value, called the measure of an indicator (ϕ_i), ranging from 0 to 1, with higher values denoting a more resilient system. Evaluating the measure of indicators is completed by simple calculations, rating scales, and yes/no questions, and do not require complex or lengthy calculations, making them advantageous over existing frameworks. Indicators of resilient design, a summary of their definition, and a definition of the measure of indicators with respect the survivability dimension are shown in Table 1. The indicators of resilient design associated with the recoverability dimension are defined in Table 2.

Each indicator should be weighted to reflect its overall contribution to system resilience. Some indicators are relevant to multiple metrics (e. g., “modularity of facilities” and “modularity of unit operations” are

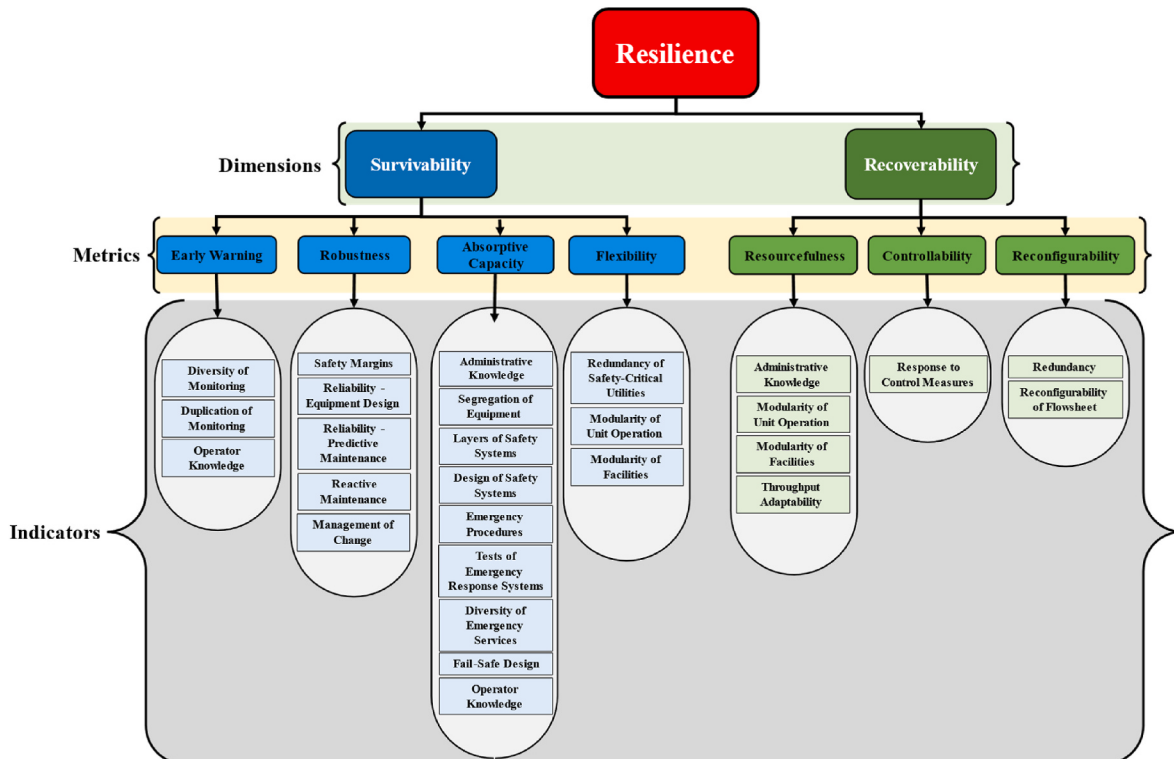


Fig. 3. The proposed model for the resilient design that encompasses the dimensions, metrics and indicators.

Table 1
Indicators of the dimension of survivability.

Metric	Indicator (i)	Summary	Measure of Indicator (φ_i)	Notes
Early Warning	Diversity of Monitoring	The measurement of multiple parameters to assess overall system health (Hewitt and Collier, 2018; Jain et al., 2018a; Hoseyni et al., 2023).	Average number of Safety-Critical Parameters (SCPs) measured in a single piece of Safety-Critical Equipment (SCE). 3+: $\varphi_1 = 1$ 2: $\varphi_1 = 0.5$ 1: $\varphi_1 = 0$	
	Duplication of Monitoring	The use of multiple sensors to measure a single system parameter (Hewitt and Collier, 2018; Hoseyni et al., 2021).	Average number of sensors monitoring a single SCP in SCE. 4+: $\varphi_2 = 1$ 2-3: $\varphi_2 = 0.5$ 1: $\varphi_2 = 0$	
	Operator Knowledge	Operators should be capable of recognizing adverse conditions quickly as they develop (Dinh, et al., 2012).	Has a training and competency management system been developed? Yes: $\varphi_3 = 1$ No: $\varphi_3 = 0$	
Robustness	Safety Margin	The use of components with higher than typical error tolerance to give increased system robustness (Yodo and Wang, 2016).	$x_4 = \frac{\left(\frac{\text{limiting conditions} - \text{normal operating}}{\text{of operation conditions}} \right)}{\text{normal operating conditions}}$ $\varphi_4 = \overline{x_4}$	This is calculated for all SCPs for all SCE in a system. x_4 is taken as the lowest value calculated of the SCPs then the average value of x_4 for all SCE gives φ_4 .
	Reliability - Equipment Design	Equipment reliability under normal operation is highly impacted by the equipment design (Hewitt and Collier, 2018).	Have all SCE designs incorporated relevant industry learning related to the reliability of each unit in the relevant setting? Yes: $\varphi_5 = 1$ No: $\varphi_5 = 0$	Industry learning must consider up-to-date and relevant information regarding equipment reliability.
	Reliability - Predictive maintenance	Predictive maintenance pre-empt's vulnerabilities to potential disruptions (Jain et al., 2018a; Hoseyni et al., 2019).	Have studies been completed and plans put in place for effective predictive maintenance of SCE? Yes: $\varphi_6 = 1$ No: $\varphi_6 = 0$	To answer 'Yes' predictive maintenance must be completed for all SCE, addressing all relevant failure nodes.
	Reactive Maintenance	Reactive maintenance must be timely and to a high standard (Hewitt and Collier, 2018).	Are the necessary staff available at all times to complete reactive maintenance? Yes: $\varphi_7 = 1$ No: $\varphi_7 = 0$	Staff availability includes those on shift and those on call.
	Management of Change	Standardized procedures should be available to ensure communication between relevant parties upon a change.	Has a management of change procedure been developed and have plans been put in place to train employees on this procedure? Yes: $\varphi_8 = 1$ No: $\varphi_8 = 0$	
Absorptive Capacity	Operator Knowledge	Operators should be knowledgeable of the process and be able to action relevant emergency procedures accurately and quickly (Dinh, et al., 2012).	Has a training and competency management system been developed? Yes: $\varphi_9 = 1$ No: $\varphi_9 = 0$	
	Administrative Knowledge	Human intervention may be required to mitigate the impacts of a disruption. Appropriate technical staff should be available at all times to complete this.	Are sufficient technical staff available at all times to address a hazard scenario? Yes: $\varphi_{10} = 1$ No: $\varphi_{10} = 0$	Staff availability includes those on shift and those on call.
	Segregation of Equipment	The potential for cascade failure is dependent on the physical availability of items of equipment to each other. Therefore, segregation (via distance and physical barriers) is advantageous for survivability (Cozzani, et al., 2007).	$x_{11} = \frac{\text{number of major units within the impact area of a single unit}}{1 - x_{11}}$ $\varphi_{11} = \frac{1 - x_{11}}{(\text{number of major units on site} - 1)}$	x_{11} is calculated for all major units which are susceptible to explosion.
	Layers of Safety Systems	Safety systems are necessary to mitigate failure consequences and avoid failure propagation. For units with multiple safety systems, each should be independent and diverse (Gill and Kadziński, 2012).	x_{12} = equipment with multiple layers of safety systems $x_{12} = 0$: $\varphi_{12} = 0$ $x_{12} > 0$: $\varphi_{12} = \frac{\text{equipment with independent and diverse layers of safety systems}}{\text{equipment with layers of safety systems}}$	
	Design of Safety Systems	Passive safety systems are preferred over active systems as have reduced vulnerability to component failure and human error (Oh, 2008).	$\varphi_{13} = \frac{\text{number of passive safety systems}}{\text{total number of safety systems}}$	All safety systems should be considered. For example, if two bunds are used within the system, these would be counted as two safety systems.
	Emergency Procedures	Emergency procedures must be in place with regular training and review to ensure they can be effectively deployed when needed (Jain et al., 2018a,b).	Are emergency response procedures in place? Yes, both on-site and potential impact area procedures: $\varphi_{14} = 1$ Yes, on-site procedures only: $\varphi_{14} = 0.5$ No: $\varphi_{14} = 0$	Potential impact area is taken as a radius of 10 km around the plant. (IAEA, 1996)
	Tests of Safety Systems	Safety systems should not only be maintained but also be regularly tested to ensure they are fit for purpose (Jain et al., 2018a,b).	Are appropriately frequent tests of emergency response equipment and systems planned? Yes: $\varphi_{15} = 1$ No: $\varphi_{15} = 0$	

(continued on next page)

Table 1 (continued)

Metric	Indicator (i)	Summary	Measure of Indicator (φ_i)	Notes
Flexibility	Diversity of Emergency Services	A system subject to an extreme hazard will often be reliant on external emergency services for survivability. Multiple providers having access to a facility mitigates a lack of availability when these services are required.	The number of branches of a particular emergency service capable of reaching the facility within a reasonable time. 3+ sources: $\varphi_{16} = 1$ 2 sources: $\varphi_{16} = 0.5$ 1 source: $\varphi_{16} = 0$	This indicator will be considered for fire brigades and hospitals, with the value taken for the particular service scoring lowest.
	Fail-Safe Design	A resilient system should be capable of suffering component failure in a safe manner that avoids failure propagation.	Has the design included fail-safe principles for every unit? Yes: $\varphi_{17} = 1$ No: $\varphi_{17} = 0$	
	Redundancy of Safety-Critical Utilities	For reliable delivery of safety-critical utilities during operation or controlled shutdown a system must have alternate utility sources available to it if the original source fails (Yodo and Wang, 2016).	Number of independent potential sources of Safety-Critical Utilities. (SCUs) 3+ sources: $\varphi_{18} = 1$ 2 sources: $\varphi_{18} = 0.5$ 1 source: $\varphi_{18} = 0$	This indicator will consider all SCUs, with the value taken for the SCU scoring lowest.
	Modularity of Unit Operations	Failure of a smaller, modular unit will have decreased consequences due to the lower volume of hazardous materials which may be released. Additionally, there is potential for production to continue at decreased capacity using unaffected units (Dinh, et al., 2012).	x_{19} = Average fraction of a process step completed over a piece of equipment $x_{19} \leq 0.5$: $\varphi_{19} = 1$ $0.5 < x_{19} \leq 0.9$: $\varphi_{19} = 0.5$ $0.9 < x_{19}$: $\varphi_{19} = 0$	This indicator only considers major unit operations.
	Modularity of Facilities	Spreading operation across multiple sites, significantly geographically separated, encourages the avoidance of an entire system being impacted by a single hazard and for operation to be continued at a decreased capacity using unaffected sites (Tian and Pistikopoulos, 2018).	x_{20} = Average Fraction of operation completed at a single sight $x_{20} \leq 0.33$: $\varphi_{20} = 1$ $0.5 < x_{20} \leq 0.9$: $\varphi_{20} = 0.5$ $0.9 < x_{20}$: $\varphi_{20} = 0$	For the purposes of resilience analysis, the fraction of operation is measured as the fraction of the total volume of materials existing at a single sight.

repeated in “Flexibility” and “Resourcefulness” metrics) and are weighted independently to reflect the various benefits they provide. The repetition draws attention to the same quality being useful for multiple aspects of resilience and having higher impact to overall resilience as a result. To determine these weights, a questionnaire is distributed to experts in process safety to rate the relative contribution of each indicator (r_i) to the resilient design of a process. The expert will be asked to rate the relative contribution they feel each indicator has towards resilient design with respect to survivability and/or recoverability with values ranging from 1 to 10 where 10 indicates large contribution. The scoring criteria is chosen as the broad form, (i.e., what contributes the most), as this allows for free interpretation and comparative analysis by the expert as the authors do not wish to influence the valuable opinions of experienced experts. This requires the participation of individuals with a good understanding of resilient engineering design. Participants may hold a variety of technical roles such as process engineers, engineering managers, and safety case engineers. Additionally, participants should be sought from a variety of sectors, ensuring wide model applicability.

The contribution weighting (ω_i) for indicator i is, then calculated as shown in Equation (2). Here r_i is the contribution score taken directly from the results of the questionnaire.

$$\omega_i = \frac{r_i}{\sum_{i=1}^{27} r_i} \quad (2)$$

Finally, the resilient design value can be quantified by summing the product of the contribution weighting (ω_i) by the measure of an indicator (φ_i) for all 27 indicators as shown in Equation (3)

$$D = \sum_{i=1}^{27} \omega_i \cdot \varphi_i \quad (3)$$

2.1.1. Cost-benefit analysis

When improving resilient design through any of the 27 indicators, only the most effective and low-cost improvements should be implemented. Therefore, consideration of relative effectiveness through a cost-benefit analysis is imperative. A questionnaire is again used for investment priority weighting, to be completed by the particular organisation adopting this model, giving a customised cost-benefit analysis. Cost rating should be completed with respect to the financial investment priorities of the organisation. This may prioritise savings in capital costs or operational costs required for actions such as training and maintenance. For each indicator (i), an investment priority weighting (α_i) is introduced that can be scored by the expert with values ranging from 1 to 10 where 10 indicates high investment priority. α_i can then be multiplied by the r_i to give a cost-benefit weighting (β_i) for each indicator (i.e., $\beta_i = r_i \times \alpha_i$). Indicators scoring highly are seen as most favourable for investment towards resilience improvements. As displayed in Fig. 4, indicators with high cost-benefit weightings are most favourable for investment towards resilience design improvements.

2.2. Potential impact (I)

The potential impact is considered to take into account the consequences of process hazards in our surroundings and communities which includes impacts on human health, the economy and the environment (CCPS, 2022). Fig. 5 gives some potential impacts of process hazards as described in CCPS, 2022. Impacts on human health entails assessing the potential direct and indirect consequences of process hazards on the health and safety of local residents and workers. Impacts on the Environment focuses on the ecological consequences of process hazards and their potential harm to the natural environment. These consequences include air and soil pollution, water contamination, threats to biodiversity, and the emission of pollutants that exacerbate the greenhouse effect, contributing to climate change. Finally, the economic impact involves the consequences that process hazards can impose to the

Table 2
Indicators of the dimension of recoverability.

Metric	Indicator (i)	Summary	Measure of Indicator (φ_i)	Notes
Resourcefulness	Modularity of Unit Operations	Production can be continued or increased through unaffected units whilst a failed unit is repaired. Additionally, small modular equipment can be manufactured and transported quickly, allowing for fast repairs (Sengupta and Yelvington, 2020).	x_{21} = Average fraction of a process step completed over a piece of equipment $x_{21} \leq 0.5 : \varphi_{21} = 1$ $0.5 < x_{21} \leq 0.9 : \varphi_{21} = 0.5$ $0.9 < x_{21} : \varphi_{21} = 0$	This indicator only considers major unit operations.
	Modularity of Facilities	Modularity of facilities gives the ability to continue or increase production at unaffected sites to make up for that lost at impacted sites.	x_{22} = Average Fraction of operation completed at a single sight $x_{22} \leq 0.33 : \varphi_{22} = 1$ $0.5 < x_{22} \leq 0.9 : \varphi_{22} = 0.5$ $0.9 < x_{22} : \varphi_{22} = 0$	For the purposes of resilience analysis, the fraction of operation is measured as the fraction of the total volume of materials existing at a single sight.
	Administrative Knowledge	Human intervention may be required to remediate system disruptions. Appropriate technical staff should be available at all times to complete this.	Are sufficient technical staff available at all times to address a hazard scenario? Yes: $\varphi_{23} = 1$ No: $\varphi_{23} = 0$	Staff availability includes those on shift and those on call.
	Throughput Adaptability	The ability to safely increase throughput across unaffected units supports equipment and facility modularity. Additionally, after a period of shutdown increasing throughput allows for a system to make up for production loss.	$x_{24} = \frac{\text{throughput under normal operation}}{\text{maximum equipment throughput}}$ $\varphi_{24} = 1 - \bar{x}_{24}$	Throughput adaptability is considered for all major equipment. The average for all major units, $\bar{x}_{24}$, will allow this indicator to be calculated.
Controllability	Response to Control Measures	A system's response to safety measures made by the control system dictates its ability to regain control and move away from unsafe conditions quickly.	x_{25} = time taken to move from limits of design space to ideal operation $\bar{x}_{25} < 1 \text{ shift} : \varphi_{25} = 1$ $1 \text{ shift} < \bar{x}_{25} < 2 \text{ shifts} : \varphi_{25} = 0.5 \bar{x}_{25} < 2 \text{ shifts} : \varphi_{25} = 0$	Design limits are considered for SCP for SCE only, with the parameter scoring the lowest taken as x_{25} for that unit. The average $\bar{x}_{25}$ for all SCE gives φ_{25} .
Reconfigurability	Redundancy	Redundancy involves the use of 'stand by' equipment that can replace failed equipment, moving the system back to normal operation.	$\varphi_{25} = \frac{\text{redundant SCE}}{\text{total amount of SCE}}$	Redundant units may be duplicates of the original with equal operating capabilities or temporary replacements.
	Reconfigurability of Flowsheet	Altering the flowsheet during dynamic operation supports other recovery capabilities e.g., deploying redundant equipment and bypassing failed equipment. This task should be simple, fast, and elegant to complete.	$\varphi_{27} = \frac{\text{number of valves allowing for potential reconfiguration}}{\text{number of lines in most basic flow sheet design}}$	

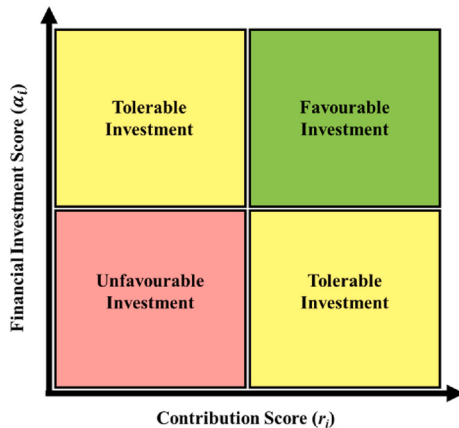


Fig. 4. A Cost-benefit analysis for assigning resilience investments.

economic well-being of the affected area, businesses, and industries by causing property damage, disrupting businesses, and so on.

To maintain model simplicity, a deterministic model is proposed to assess the wide range of possible hazards and their consequences within each of the three categories shown in Fig. 5. Hence, a system's worst-case scenario is assessed where all existing safety systems are assumed to have no effect. As this method is not dependent on highly specific hazards and their effects, the use of the model across a wide range of process systems is straightforward. Furthermore, as many different hazards will have similar consequences and impacts on a system, this simplified approach will deliver a similar level of accuracy. This model

comprehends the potential for impact through two general groups; potential for economic impact and potential for impact on human health and the environment.

2.2.1. Potential for economic impact (I_{eco})

Potential for economic impact is taken as a function of potential damage to the facility and loss of production (e.g., due to loss of plant functionality or necessary plant quarantines) leading to loss of revenue. Potential damage to the facility is quantified by the system's capital cost, assuming a BDBE may have the capability to destroy an entire facility however appreciates that this will not always occur. Capital cost is used as a standardized and easily found value, giving a good proxy measure of the potential economic impact due to damage to the facility. To describe the economic impact due to loss of production, the yearly revenue is used. This assumes a BDBE may have the capability to halt production for a year but appreciates that production may be impacted for any amount of time. Again, this offers a standardized and easily found value giving a snapshot of this quality. Therefore, the potential for economic impact (I_{eco}) is described by Equation (4) where CC is the capital cost (\$) and R is the yearly revenue (\$/year).

$$I_{eco} = CC + R \quad (4)$$

2.2.2. Potential impact on human health and the environment ($I_{H\&E}$)

The potential impact on human health and the environment is composed of 3 main sections: chemical hazard potential, the human health impact rating, and the environmental impact rating. The separate assessment of these offers the individual comprehension of each factor before they are combined to give the overall potential impact.

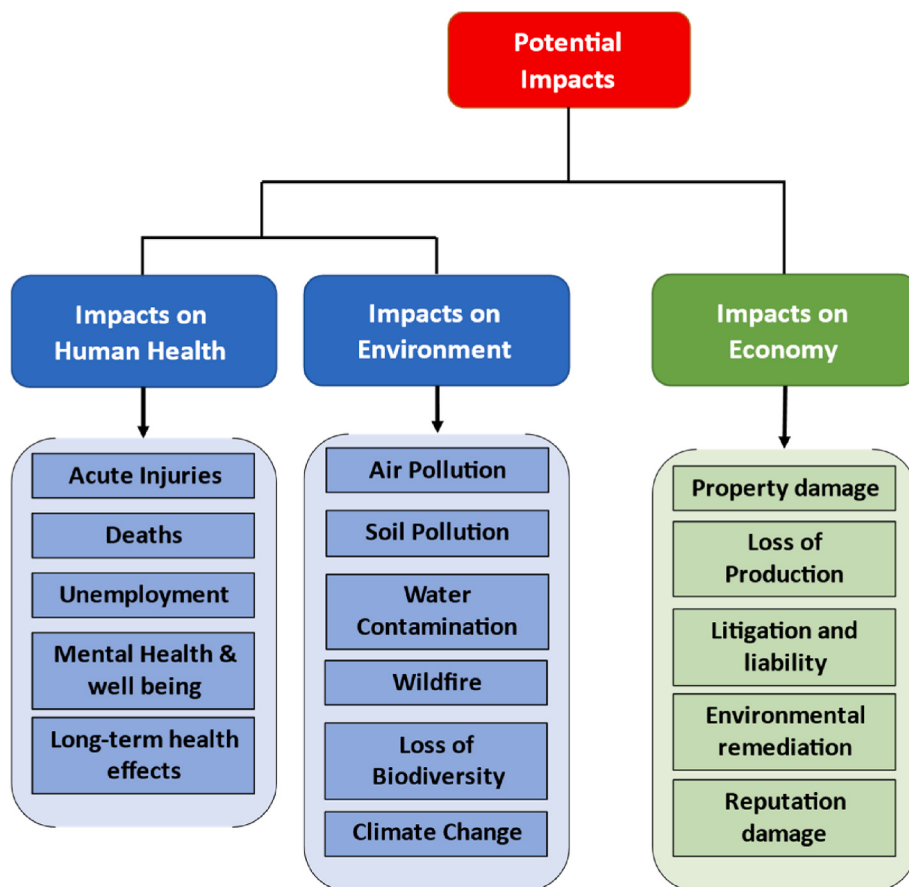


Fig. 5. Potential impacts of process hazards.

2.2.2.1. Chemical Hazard Potential. To assess the potential for impact on human health and the environment, it is important to consider the chemical inventory present on a plant (including stored quantities) and the physical states in which they are present. The hazards associated with each material are measured by the Chemical Hazard Potential (CHP), an industrially accepted concept used to reflect physio-chemical, toxic, and environmental hazards (Zhang, et al., 2019). The calculation of CHP for a system is taken from the approach used by the Nuclear Decommissioning Authority (NDA) which utilizes Control of Major Accident Hazard (COMAH) limits presented in NDA, 2011 which quantitatively reflect relative hazard by assigning scores to all hazardous properties a material may have. Relative hazard is quantitatively described by COMAH limits presented for each hazard which a material may pose (e.g., oxidising gas, corrosive, highly corrosive, respiratory tract irritation all having values assigned). Equation (5) shows the calculation of CHP where FF_M is the form factor, CF is the control factor, and C_{Inv} is the COMAH inventory (a function of the COMAH limit), calculated for each k chemical present at a facility. If a material exists in multiple phases, then the CHP of each phase must be calculated due to the different form factors and potentially different hazards associated with each phase.

$$CHP = \sum_{j=1}^k CHP_j = \sum_{j=1}^k \frac{(C_{Inv})_j \times (FF_M)_j}{CF_j} \quad (5)$$

The phase of materials dictates the potential for loss of containment as this will control the ease that they can release to the environment where they can contaminate surroundings and be exposed to adverse conditions (e.g., flammable material being exposed to an ignition source). Additionally, the phase of a material dictates the range and rate at which it can travel when containment is lost. These characteristics are

described by the form factor (FF_M), which has been modified from the form factor values used by the NDA. This is to reflect a liquid's increased potential for loss of containment and increased rate and range of movement once containment is lost, compared to less mobile sludges and solids. FF_M values are shown in Table 3.

Furthermore, the control factor (CF), shown in Table 4, is described based on the duration that a material will be left on site without monitoring or intervention.

The COMAH inventory for each chemical, k , $(C_{Inv})_k$ is calculated by Equation (6). Here, m_k is the mass of k th chemical in tonnes and c_i is its COMAH limit (found using COSHH databanks).

$$(C_{Inv})_k = 10^{11} \times \frac{m_k}{c_k} \quad (6)$$

For a batch or semi-batch system where the materials present on site are variable, it is suggested to calculate CHP for the maximum volume of a given chemical present at any time during operation. This takes a worst-case scenario approach, in line with the resilience concept, where the maximum amount of hazardous materials is assumed to exist at a facility in conjunction.

Table 3
Modified form factor, FF_M (NDA, 2011).

Phase	FF_M
Gas	1×10^0
Liquid	5×10^{-1}
Sludge	1×10^{-1}
Powders	1×10^{-1}
Discrete solids	1×10^{-5}
Large monolithic and activated compounds	1×10^{-6}

Table 4
Control factor, CF (NDA, 2011).

Time material is left without monitoring or intervention	CF
Hours or less	1×10^0
Days	1×10^1
Weeks	1×10^2
Months	1×10^3
Years	1×10^4
Decades	1×10^5

2.2.2.2. Human health impact rating. The potential consequences of a system's CHP on human health can be properly described by considering the population surrounding the facility with the human health impact rating (H). The population is divided into two groups, namely the critical population (P_c) and the wider population (P_w), based on the severity of the consequence and distance from the facility. P_c includes the staff on-site and those living around the facility, who are at the highest risk of direct impact. P_w includes those susceptible to lower severity impacts, up to 10 km from the plant (IAEA, 1996). The human health impact rating is a combination of these two groups, with appropriate weighting given to P_c . As shown in Equation (7), H is the combination of the two population groups where an index of 5 is used to ensure H is appropriately sensitive to the lower value of P_c compared to P_w .

$$H = P_c^5 + P_w \quad (7)$$

2.2.2.3. Environmental impact rating. The environmental impact rating (E) is used to measure the potential consequences for the environment by considering the plant's proximity to ecosystems that would be affected by a process disaster. Biodiversity is used as an effective descriptor of environmental health and is measured within a 10 km radius around the plant using data from the group "Key Biodiversity Areas (KBAs)" (KBA, 2022). This data is plotted on a global map with a color scale, and an E rating has been assigned, as shown in Table 5, to each area based on the level of biodiversity, with a higher E denoting a richer environment.

The human health and environmental impact ratings can then be combined with the CHP to give the overall potential for impact on human health and the environment. This is shown in Equation (8).

$$I_{H+E} = CHP(H + E) \quad (8)$$

From Equations (4) and (8) the final equation form describing the potential impact on the economy, human health, and the environment is shown in Equation (9).

$$I = I_{eco} + I_{H+E} \quad (9)$$

2.3. Vulnerability

Resilience engineering should also acknowledge the need of comprehending and resolving vulnerabilities to avoid or minimize the impact of failures. In order to do this, possible sources of vulnerability

must be identified, and strategies must be developed to improve the system or organization's capacity to recognise and address them.

The proposed vulnerability approach is also completed through a deterministic approach independent of the initiating events and instead, based on the worst-case scenario consequences. To quantify system vulnerability to severe events cascade failure is considered which would enable a system to suffer uncontrolled consequences of an initial impact. Hence, a system with a high risk of cascade failure will be highly vulnerable to severe and unexpected events.

Combustible substances are particularly susceptible to cascade failure, making up 89% of substances involved in cascade failure events (Darbra, et al., 2010). Therefore, vulnerability to uncontrolled events is quantified by the mass of flammable and explosive material present in a plant. Vulnerability is considered without regard for the safety systems and procedures in place to mitigate against fire and explosions to consider a worst-case scenario event. CHP analysis is modified to express system vulnerability to each of the two major initiating modes of fire and explosion which are (Crowl and Louvar, 2001):

- The ignition of flammable or explosive substances (including dust)
- Explosion due to excess pressure exerted by gasses causing the mechanical failure of the containment vessel

2.3.1. Vulnerability to fire and explosion due to ignition

COSHH data is used to identify all flammable and explosive chemicals present in a process plant (i.e., n chemicals). Using a modified form of Equations (5) and (6), the CHP due to ignition (CHP_{ign}) can be found to quantify the vulnerability of a system to this failure mode. The COMAH inventory of each flammable and explosive chemical present on a process plant, n , ($C_{Inv,ign}$) $_n$ is found by using the COMAH limit with respect to flammability and/or explosion hazards only (c_n) as shown in Equation (10).

$$(C_{Inv,ign})_n = 10^{11} \frac{m_n}{c_n} \quad (10)$$

The remaining requirements for fire or explosion, oxygen, and heat/ignition sources, aren't specifically considered in this analysis. This is because these elements are assumed to be readily abundant in and around a plant as atmospheric oxygen is always available and ignition sources are difficult to exclude in an industrial setting. CHP_{ign} is quantified using Equation (11).

$$CHP_{ign} = \sum_{j=1}^n (CHP_{ign})_j = \sum_{j=1}^n \frac{(C_{Inv,ign})_j \times (FF_M)_j}{CF_j} \quad (11)$$

2.3.2. Vulnerability to explosion due to excess pressure

For the consideration of vulnerability due to excess pressure, an assumption is made to simplify the analysis that this event would only occur due to the heating of gas and that this uncontrolled heating will only occur due to a runaway exothermic reaction. This is a common initiator of explosions of this nature with 167 serious accidents involving runaway reactions occurring between 1980 and 2001 (Crowl and Louvar, 2001).

When considering uncontrolled heating of gasses upon a runaway reaction, a process that exerts heat at a slower rate will have a longer time before an explosion occurs. With more time for intervention to control a process, where safety features can be put to use more effectively, a system will be less vulnerable to explosion. Therefore, it is useful to introduce a term describing this dependency on the rate of heat production. For an exothermic reaction, R , the heat of reaction (Q_R), giving the energy expelled per mole reacted, effectively describes the rate of heat production. It should be noted that no rate factor is used for vulnerability due to ignition as this occurs instantaneously when fuel is exposed to ignition sources in oxygen.

To describe this quality, the CHP of explosion due to excess pressure

Table 5
Environmental impact rating assigned to the KBA scale (KBA, 2022).

KBA Colour Scale	Environmental Impact Rating, E
	1×10^1
	1×10^2
	1×10^3
	1×10^4
	1×10^5
	1×10^6
	1×10^7

(CHP_{exp}) is found for all gaseous materials susceptible to a runaway reaction (i.e., those held in a vessel accommodating an exothermic reaction, D). These vessels, and the material held in them, must be identified and the risk of explosion due to gas being heated is used to find the COMAH limit for all relevant material with respect to this hazard only; hence $c_l = 150$ as specified by NDA (NDA, 2011). COMAH inventory with respect to explosion due to excess pressure ($C_{Inv,exp}$) _{l} is quantified using a modified form of Equation (5) shown in Equation (12).

$$(C_{Inv,exp})_l = 10^{11} \frac{m_l}{150} \quad (12)$$

CHP_{exp} is then found using a modified form of Equation (5) shown in Equation (13).

$$CHP_{exp} = \sum_{j=1}^l (CHP_{exp})_j = \sum_{j=1}^l \frac{(C_{Inv,exp})_j \times (FF_M)_j}{CF_j} \times (Q_r)_j \quad (13)$$

The final equation describing vulnerability to uncontrolled events is the simple addition of Equations (11) and (13) as shown in Equation (14).

$$V = CHP_{ign} + CHP_{exp} \quad (14)$$

3. Case studies

The application of the developed model is demonstrated in two case studies in order to assess the results and iteratively adjust the model to ensure good sensitivity to all factors considered.

Case study 1 is a production process for ammonia and urea located in Houston, Texas. This process produces 300,000 tonnes of ammonia and 280,000 tonnes of urea per year and relies on hydrogen obtained from natural gas processing (Scattergood, et al., 2020). While gases are the primary materials processed, liquids and solids are also handled. The block flow diagram of this process is shown in Fig. 6.

Case study 2 is a p-aminophenol production plant that produces 22,000 tonnes of p-aminophenol per year by reacting nitrobenzene with hydrogen gas, which also yields aniline as a by-product (Ghoroi, et al., 2021). The system primarily handles liquids, but gas is also processed. Certain assumptions were made, including the central location of the facility in the Mumbai-Pune industrial area, one of India's major industrial regions, and a typical industry-standard site layout. Fig. 7 shows the simplified block diagram of this system.

3.1. Results and discussion

The results of the indicator contribution and cost-benefit evaluation questionnaires are shown in Table 6. This shows the contribution of each

indicator to resilient design as the contribution score (r_i) with respect to a non-specified chemical process, and investment priorities as a weighting (α_i) with respect to the above case studies. Upon further distribution of these questionnaires, the rating of each indicator will be taken as an average, or alternatively, results from particular experts can be given a higher weighting to reflect knowledge and experience.

At this stage the questionnaire has been completed by a single process safety expert with extensive experience in the industrial agricultural sector. Wider distribution of this questionnaire to experts across a variety of industries is required to ensure the models applicability to a wide range of process plants. Questionnaire distribution methods may include conference workshops, approaching businesses directly, or through discipline specific governing bodies e.g. the IChemE.

After collecting the contribution scores (r_i) from the expert judgment, the weighting of each indicator (ω_i) is then calculated as shown in Table 6 using Equation (2). Cost Benefit Weighting (β_i) is also calculated as the multiplication of r_i and α_i .

From the analysis of contribution ratings, it is seen that all indicators have a significant contribution to resilience. With a scale of 0–10 (with 10 denoting high contribution), the average rating was 7.6, with a range from 3 to 10. Cost-benefit ratings have an initial scale from 0 to 100 (with 100 denoting the most favourable indicators for investment), however, since some indicators are relevant to multiple metrics of resilience, their cost-benefit ratings are added. Therefore, the average cost-benefit rating was 74, ranging from 25 to 200. The potentially large benefit to resilience by investing in indicators contributing to multiple metrics of resilience is clearly displayed as the indicators receiving the highest cost-benefit ratings are:

1. Operator Knowledge (contributing to the metrics of early warning and absorptive capacity)
2. Modularity of Facility (contributing to the metrics of flexibility and resourcefulness)

The initial resilience equation shown in Equation (1) is modified to give Equation (15) to scale the model around two of the three dimensional values of capital cost (CC) and annual revenue (R). This is completed as these values give a good base to scale resilience around. It must be noted that this model does not give mathematical continuity with respect to units, however, as a tool for the qualitative analysis of resilience, this is seen as permissible.

$$\Psi = \frac{10^{17} \times D}{[(CC + R) + 10^{-8} \times CHP(H + E)] \times [10^{-2} CHP_{ign} + 10^{-3} CHP_{exp}]} \quad (15)$$

The resilience results of this model have been broken down and

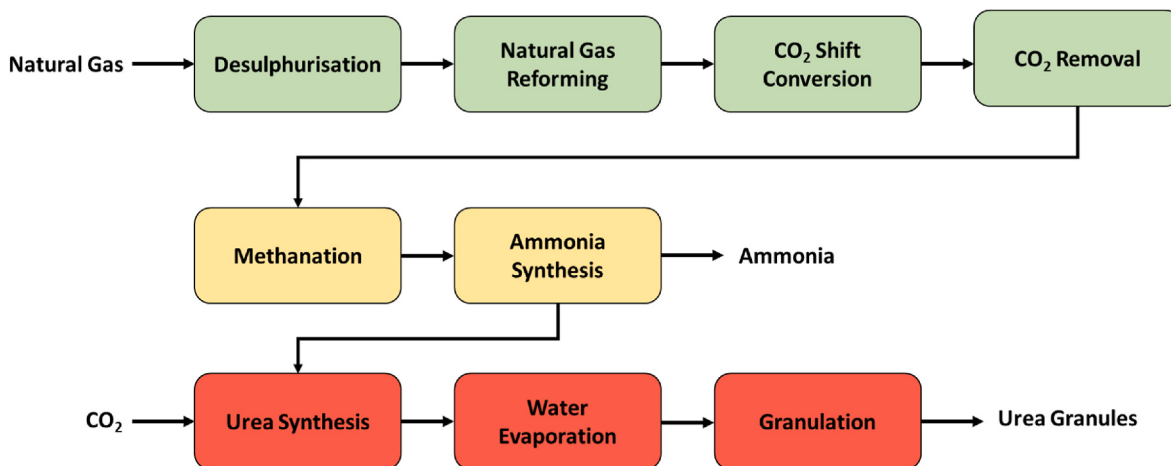


Fig. 6. Block flow diagram of an ammonia and urea production process (Scattergood, et al., 2020).

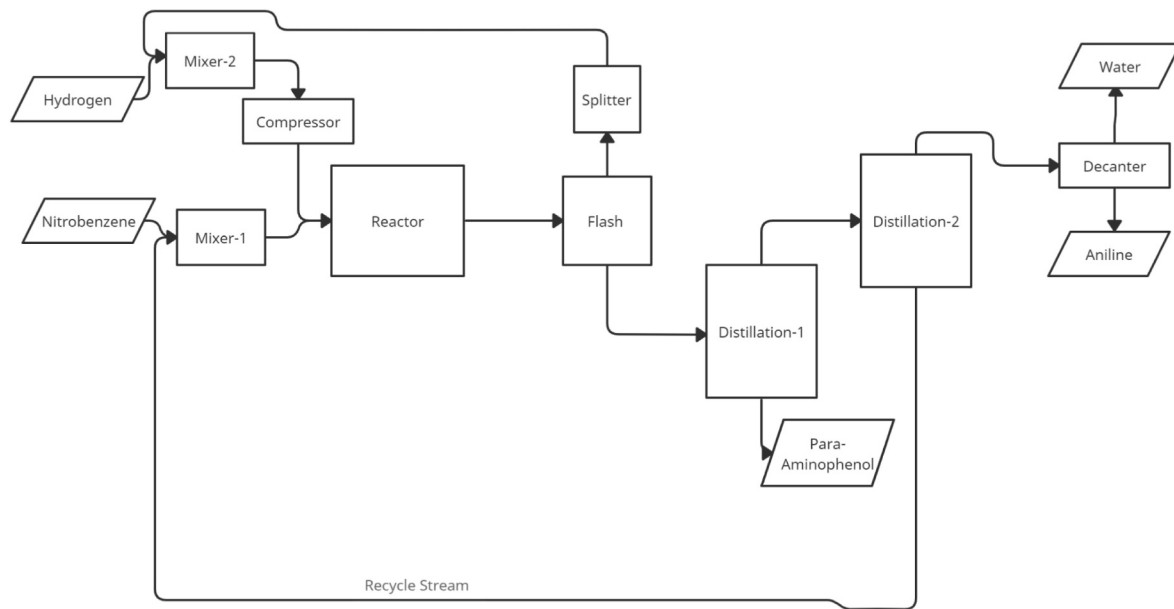


Fig. 7. Simplified block diagram of a p-aminophenol production process (Ghoroi, et al., 2021).

Table 6

Completed questionnaire for the contribution score (r_i) and (α_i), calculated weighting of each indicator (ω_i), and cost-benefit weighting (β_i).

Resilience Metric	i	Indicator (i)	Contribution Score (r_i)	weighting of each indicator (ω_i)	Financial Investment Score (α_i)	Cost-Benefit Weighting (β_i)
Early Warning	1	Diversity of Monitoring	8	0.0379	8	64
	2	Duplication of Monitoring	7	0.0332	7	49
	3	Operator Knowledge	10	0.0474	10	200
Robustness	4	Safety Margin	8	0.0379	8	64
	5	Reliability - Equipment Design	5	0.0237	5	25
	6	Reliability - Predictive Maintenance	3	0.0142	10	30
Absorptive Capacity	7	Reactive Maintenance	8	0.0379	5	40
	8	Management of Change	10	0.0474	10	100
	9	Operator Knowledge	10	0.0474	10	200
	10	Administrative Knowledge	5	0.0237	3	30
	11	Segregation of Equipment	8	0.0379	8	64
	12	Layers of Safety Systems	10	0.0474	10	100
	13	Design of Safety Systems	10	0.0474	10	100
	14	Emergency Procedures	10	0.0474	10	100
	15	Tests of Emergency Response Systems	10	0.0474	10	100
Flexibility	16	Diversity of Emergency Services	8	0.0379	8	64
	17	Fail-Safe Design	10	0.0474	10	100
	18	Redundancy of Safety-Critical Utilities	10	0.0474	10	100
	19	Modularity of Unit Operation	5	0.0237	5	50
Resourcefulness	20	Modularity of Facilities	8	0.0379	8	128
	21	Modularity of Unit Operation	5	0.0237	5	50
	22	Modularity of Facilities	10	0.0474	8	128
	23	Administrative Knowledge	5	0.0237	3	30
Controllability	24	Throughput Adaptability	5	0.0237	8	40
	25	Response to Control Measures	8	0.0379	8	64
Reconfigurability	26	Redundancy	8	0.0379	8	64
	27	Reconfigurability of Flowsheet	7	0.0332	7	49

summarised in Table 7 for both case study 1 and 2. Detailed calculations and results of this model are shown in the appendix.

The results show that case study 2 scored significantly lower for the indicator of resilient design, scoring 0.121 compared to 0.214 of case study 1. This is attributed to a limited consideration to technical factors beyond that of the most basic design, and little to no consideration of administrative factors. With no thought to many indicators, a considerable amount scored very low, consequently giving a low score of resilient design. This highlights the importance of resilience consideration at the early design stages to ensure a system is created with

resilience at its foundations.

On the other hand, despite case study 1 scoring higher for resilient design, it is observed that a considerable number of indicators scored low (19 out of 27 indicators scored 0 as shown in Table A-1 of the appendix). This is despite a good amount of thought being assigned to process safety with a detailed HAZID and LOPA being completed for this specific case study. This shows that design basis hazard analysis does not extend well to give resilience to BDBEs. This is significant as displays that industry-standard hazard analysis is not sufficient to consider or address resilience and a specified analysis is essential before

Table 7

Resilience results of case study 1 and 2.

Parameter	Case Study 1	Case Study 2
Indicator of resilient design (<i>D</i>)	2.14×10^{-1}	1.21×10^{-1}
CC (\$)	5.77×10^8	2.52×10^7
<i>R</i> (\$/year)	7.30×10^7	2.37×10^7
<i>CHP</i>	1.32×10^{10}	4.10×10^{10}
<i>H</i>	5.51×10^5	6.29×10^6
<i>P_c</i>	4.00×10^0	5.00×10^0
<i>P_w</i>	5.50×10^5	6.28×10^6
<i>E</i>	1.00×10^2	5.50×10^1
<i>I_{eco}</i>	6.50×10^8	4.89×10^7
<i>I_{H&E}</i>	7.27×10^7	2.58×10^9
Potential Impact (<i>I</i>)	7.23×10^8	2.66×10^9
<i>CHP_{ign}</i>	8.79×10^9	1.80×10^{10}
<i>CHP_{exp}</i>	1.38×10^{11}	3.07×10^{11}
Vulnerability (<i>V</i>)	2.26×10^8	4.87×10^8
Resilience (<i>Ψ</i>)	1.31×10^{-1}	9.34×10^{-3}

implementation of any process system. This stresses the requirement for the use of the presented model in industry.

Case study 2 scores significantly higher for potential impact (2.66×10^9 compared to 7.23×10^8 scored by case study 1) despite a lower potential for economic impact (see *I_{eco}* at Table 7). A factor contributing to this higher potential impact is the *CHP* which is notably larger to that of case study 1. This higher *CHP* is due to a much higher volume of material of a similar hazard level present on-site for case study 2, offset by this material being primarily liquid over the gas predominantly handled in case study 1. However, the factor most strongly influencing case study 2 scoring high for potential impact is the extremely high population density (*P_w*) in the Mumbai-Pune Industrial Area, giving a wider population value of 6.28 million people. This places the site in an area with significant potential impact to human health as the population density here is over 300 times the global average and over 10 times that of Houston Texas, the location of case study 1.

Finally, the vulnerability of case study 2 is around twice that of case study 1 (4.87×10^8 compared to the 2.26×10^8 scored by case study 1). This is for similar reasons as discussed for potential impact which cause a higher *CHP* for case study 2. The resulting drastically larger potential impact and slightly larger vulnerability for case study 2 compared to case study 1 validates the model's sensitivity to relevant components of resilience.

The resulting resilience values of case study 1 and 2, scoring 0.131 and 0.00934 respectively, show a stark difference with two orders of magnitude between them. This effectively displays the impact of the combination of factors contributing to system resilience and outlines that case study 1 is much more resilient than case study 2.

3.2. Improvements to system resilience

The design of case study 2 needs to be modified in order to improve the system's resilience. This is done through two different approaches to compare impact. Approach 1 makes the system more resilient by the improvement of resilient design where the top 3rd of indicators scoring highest cost-benefit weighting (β_i) are each improved by modifying the system so that the mentioned indicators (φ_i) can obtain the maximum; equal to 1. These indicators will lie closer to the top right corner of Fig. 4 hence are favourable for investments towards. The selected indicators are:

- Operator Knowledge
- Management of Change
- Layers of Safety Systems
- Design of Safety Systems
- Emergency Procedures
- Tests of Emergency Response Systems and Equipment
- Fail-Safe Design

- Redundancy of Safety-Critical Utilities
- Modularity of Facility

It should be noted that in practice, small incremental improvements will be made to resilient design, over the group improvement of multiple indicators. This will start with indicators of highest cost-benefit weighting, and an iteration of resilience calculated after each change. This is completed with the aim of reaching a permissible level of resilience with the minimum investment required.

Approach 2 is defined to make a more resilient case by the hypothetical movement of this plant to the location of case study 1, Houston, Texas. This significantly reduces the human health impact rating, a large contributor to the low resilience of case study 2. Resilience and its basic contributing factors for each approach are shown in Table 8.

Approach 1 displays a significant increase in resilience when improving resilient design via only a handful of indicators (from 0.00934 to 0.0378). These changes will of course have associated costs, but beyond this will have a relatively low impact on the system design. However, when this is compared to approach 2, it is clear that improvement to significant contributors to potential impact and/or vulnerability can give a much higher contribution to resilience. Making improvements via this strategy however, can involve dramatic changes to a system design. Approach 2 requires a new plant location to be sought, an act that would cause serious disruption to the planning and implementation of this system. Changes to other factors of potential impact and/or vulnerability would incur similar levels of disruption. For example, to decrease the *CHP*, the strategy via which processes are completed must be significantly altered or the chemistry changed altogether. Therefore, in practice the pathway to achieve improved resilience must be carefully considered.

To employ this model widely across industry further work is recommended by applying the methodology to a wide and diverse range of process designs to validate the scaling of the model as shown in Equation (15) and ensure applicability across multiple sectors. Extensive completion of case studies would also allow for a more in-depth analysis of the model results allowing for the potential introduction of a red, amber, green status associated with values of resilience. Attaching context to the novel measure of resilience is critical to provide clear and accessible comprehension of model results.

4. Conclusion

In this paper, a novel qualitative model is provided to assess resilience in the process industry, providing an effective snapshot of system resilience whilst clearly indicating the contributing factors. The model defines resilience via three key attributes, 1) resilient design, 2) potential impacts considering economic, human health and environmental consequences, 3) vulnerability to BDBEs. The application of the methodology is demonstrated in two case study process plants.

This model is intended for wide application throughout the process industry and does not require an in-depth understanding of a system or of process safety to complete. This is to offer a methodology that can be carried out by the competencies available to a project, giving a strategy for the accessible and widespread understanding of resilience. However, to highlight the limitations of the work, it is worth mentioning that the

Table 8

Case Study 2, improved Resilience with two different approaches.

	Before improvement	Approach 1	Approach 2
Indicator of resilient design (<i>D</i>)	0.121	0.491	0.121
Potential Impact (<i>I</i>)	2.66×10^9	2.66×10^9	2.76×10^8
Vulnerability (<i>V</i>)	4.87×10^8	4.87×10^8	4.87×10^8
Resilience (<i>Ψ</i>)	0.00934	0.0378	0.09

model requires more extensive data collection to be seen as mature. This is required in the form of input from process safety experts on the contribution of indicators of resilient design, and the application of the model to a variety of case studies to ensure a robust reflection of resilience levels across a wide range of process systems. Additionally, further data collection will provide industrial context to calculated resilience values, presenting clear and comprehensible outputs of the model for the standardized measurement of resilience across process sectors. In future research endeavors, there is an opportunity to broaden the scope of resilient design indicators to include the dynamic characteristics of the system. This expansion would involve addressing aspects that were either not previously covered or remained unknown in the context of our current research. By pursuing this direction, we can work towards reducing uncertainties and improving the indicators' ability to effectively incorporate elements such as human factors and error into the broader framework of system resilience.

Once mature, this tool can sit alongside and integrate with established process safety methodologies (such as HAZOP, QRA, and LOPA) and has the power to transform resilience from an ambiguous concept into a simple and widely used design strategy, vital for its practical application throughout the process industry.

Appendix

Section 1: Case Study Calculations (Case Study 1)

Table A-1 shows the detail that is used to calculate the indicator of resilient design for case study 1, using Equation (3) and values provided by expert judgment provided in Table 6.

Table A-1
Indicators of Resilient Design (Case Study 1)

<i>i</i>	Indicator (<i>i</i>)	Measure of indicator (φ_i)	Contribution weighting (ω_i)	$\omega_i \cdot \varphi_i$
1	Diversity of Monitoring	0.5	0.0379	0.0190
2	Duplication of Monitoring	0	0.0332	0
3	Operator Knowledge	0	0.0474	0
4	Safety Margin	0	0.0379	0
5	Reliability - Equipment Design	0	0.0237	0
6	Reliability - Predictive Maintenance	1	0.0142	0.0142
7	Reactive Maintenance	1	0.0379	0.0379
8	Management of Change	0	0.0474	0
9	Operator Knowledge	0	0.0474	0
10	Administrative Knowledge	0	0.0237	0
11	Segregation of Equipment	0	0.0379	0
12	Layers of Safety Systems	1	0.0474	0.0474
13	Design of Safety Systems	0.167	0.0474	0.0079
14	Emergency Procedures	0	0.0474	0
15	Tests of Emergency Response Systems	0	0.0474	0
16	Diversity of Emergency Services	1 ^a	0.0379	0.0379
17	Fail-Safe Design	1	0.0474	0.0474
18	Redundancy of Safety-Critical Utilities	0	0.0474	0
19	Modularity of Unit Operation	0	0.0237	0
20	Modularity of Facilities	0	0.0379	0
21	Modularity of Unit Operation	0	0.0237	0
22	Modularity of Facilities	0	0.0474	0
23	Administrative Knowledge	0	0.0237	0
24	Throughput Adaptability	0.1	0.0237	0.00237
25	Response to Control Measures	0	0.0379	0
26	Redundancy	0	0.0379	0
27	Reconfigurability of Flowsheet	0	0.0332	0
Resilient Design (<i>D</i>)				0.214

^a 3 Fire stations within 5 miles of the facility and 3 hospitals within 13 miles of the facility.

The values that is used to quantify the CHP value of case study 1, using Equations (5) and (6) and Tables 3–4, are shown in Table A-2.

CRediT authorship contribution statement

Freya Vesey: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Seyed Mojtaba Hoseyni:** Conceptualization, Validation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Joan Cordiner:** Conceptualization, Methodology, Validation, Writing – review & editing, Visualization, Supervision, Project administration.

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.

Data availability

Data will be made available on request.

Table A-2

Data for the Calculation of CHP (Case Study 1)

Chemical (k)	m_k (tonnes)	FF_M	CF	c_k	CHP_k
Methane	0.351	1	1	10	3,510,000,000
Ethane	0.0455	1	1	10	455,000,000
Propane	0.0228	1	1	10	228,000,000
Butane	0.00910	1	1	10	91,000,000
Pentane +	0.00227	1	1	200	1,140,000
Nitrogen	0.116	1	1	150	77,247,000
Carbon dioxide	0.164	1	1	150	110,000,000
Water (l)	0.113	0.5	1	N/A	N/A
Water (g)	0.129	1	1	150	85,800,000
Carbon monoxide	0.0455	1	1	10	455,000,000
Hydrogen	0.403	1	1	5	8,070,000,000
Ammonia (l)	0.0797	0.5	1	150	26,600,000
Ammonia (g)	0.0156	1	1	50	31,200,000
Hydrogen sulphide	0.00103	1	1	5	20,500,000
mercaptan sulphur	0.000729	1	1	10	7,290,000
Oxygen	0.000000312	1	1	200	156
Urea	0.155	0.00001	1	N/A	N/A
Formaldehyde	0.000806	0.5	1	5	8,060,000
MEA	0.00789	0.5	1	150	2,630,000
				CHP	13,200,000,000

The vulnerability to fire and explosion due to ignition in case study 1 is quantified using Equations (10) and (11) and Tables 3–4 with the detailed values listed in Table A-3.

Table A-3Data regarding flammable and explosive materials for the calculation of CHP_{ign} (Case Study 1)

Chemical (n)	m_n (tonnes)	FF_M	CF	c_n	$(CHP_{ign})_n$
Methane	0.351	1	1	10	3,507,000,000
Ethane	0.0455	1	1	10	455,000,000
Propane	0.0228	1	1	10	228,000,000
Butane	0.00910	1	1	10	91,000,000
Pentane +	0.00227	1	1	5000	45,500
Carbon monoxide	0.0455	1	1	10	455,000,000
Hydrogen	0.403	1	1	10	4,030,000,000
Hydrogen sulphide	0.00103	1	1	10	10,300,000
Mercaptan sulphur	0.000729	1	1	10	7,290,000
Oxygen	0.000000312	1	1	5000	6.24
Formaldehyde	0.000806	0.5	1	5000	8060
				CHP_{ign}	87,900,000,000

The vulnerability to explosion due to excess pressure in case study 1 is quantified using Equations (12) and (13) and Tables 3–4 with the detailed values listed in Table A-4.

Table A-4Data regarding units facilitating exothermic reactions which hold gaseous materials for the calculation of CHP_{exp} (Case Study 1)

Unit (l)	m_l (tonnes)	FF_M	CF	c_l	$(Q_r)_l$ (kJ/mol)	$(CHP_{exp})_l$
RF-100	0.163	1	1	150	41.2	4,490,000,000
RF-101	0.189	1	1	150	844	106,000,000,000
R-100	0.0162	1	1	150	41.2	445,000,000
R-101	0.0165	1	1	150	41.2	453,000,000
R-102	0.0881	1	1	150	370	21,700,000,000
R-103	0.0744	1	1	150	92.4	4,580,000,000
					CHP_{exp}	138,000,000

Section2: Case Study Calculations (Case Study 2)

Table A-5 shows the detail that is used to calculate the indicator of resilient design for case study 2, using Equation (3) and values provided by expert judgment provided in Table 6.

Table A-5

Indicators of Resilient Design and Cost-benefit analysis(Case Study 2)

i	Indicator (i)	Measure of indicator (φ_i)	Contribution weighting (ω_i)	$\omega_i \varphi_i$
1	Diversity of Monitoring	0	0.0379	0
2	Duplication of Monitoring	0	0.0332	0

(continued on next page)

Table A-5 (continued)

<i>i</i>	Indicator (<i>i</i>)	Measure of indicator (φ_i)	Contribution weighting (ω_i)	$\omega_i \cdot \varphi_i$
3	Operator Knowledge	0	0.0474	0
4	Safety Margin	0	0.0379	0
5	Reliability - Equipment Design	0	0.0237	0
6	Reliability - Predictive Maintenance	1	0.0142	0.0142
7	Reactive Maintenance	1	0.0379	0.0379
8	Management of Change	0	0.0474	0
9	Operator Knowledge	0	0.0474	0
10	Administrative Knowledge	0	0.0237	0
11	Segregation of Equipment	0 ^a	0.0379	0
12	Layers of Safety Systems	0	0.0474	0
13	Design of Safety Systems	1	0.0474	0.0474
14	Emergency Procedures	0	0.0474	0
15	Tests of Emergency Response Systems	0	0.0474	0
16	Diversity of Emergency Services	0.5 ^b	0.0379	0.019
17	Fail-Safe Design	0	0.0474	0
18	Redundancy of Safety-Critical Utilities	0	0.0474	0
19	Modularity of Unit Operation	0	0.0237	0
20	Modularity of Facilities	0	0.0379	0
21	Modularity of Unit Operation	0	0.0237	0
22	Modularity of Facilities	0	0.0474	0
23	Administrative Knowledge	0	0.0237	0
24	Throughput Adaptability	0.1	0.0237	0.00237
25	Response to Control Measures	0	0.0379	0
26	Redundancy	0	0.0379	0
27	Reconfigurability of Flowsheet	0	0.0332	0
Resilient Design (<i>D</i>)				0.121

^a Assumed industry-standard equipment spacing (Sinnott, 2005).

^b 2 Fire stations within 4 km and 2 hospitals within 5 km of the facility.

The values that is used to quantify the CHP value of case study 2, using Equations (5) and (6) and Tables 3–4, are shown in Table A-6.

Table A-6

Data for the Calculation Of CHP (Case Study 2)

Chemical (<i>k</i>)	m_k (tonnes)	FF_M	CF	c_k	CHP_k
Nitrobenzene	1.85	0.5	1	50	1,850,000,000
Hydrogen	1.80	1	1	5	35,900,000,000
Water (l)	5.101	0.5	1	N/A	N/A
Water (g)	1.27	1	1	150	912,000,000
Aniline	1.77	0.5	1	50	1,770,000,000
Para-Aminophenol	1.17	0.5	1	100	583,000,000
				CHP	41,000,000,000

The vulnerability to fire and explosion due to ignition in case study 2 is quantified using Equations (10) and (11) and Tables 3–4 with the detailed values listed in Table A-7.

Table A-7

Data regarding flammable and explosive materials for the Calculation of CHP_{ign} (Case Study 2)

Chemical (<i>n</i>)	m_n (tonnes)	FF_M	CF	c_n	$(CHP_{ign})_n$
Nitrobenzene	1.85	0.5	1	5000	18,500,000
Hydrogen	1.79	1	1	10	17,950,000,000
Aniline	1.77	0.5	1	5000	17,700,000
				CHP_{ign}	18,000,000,000

The vulnerability to explosion due to excess pressure in case study 2 is quantified using Equations (12) and (13) and Tables 3–4 with the detailed values listed in Table A-8.

Table A-8

Data regarding units facilitating exothermic reactions which hold gaseous materials for the calculation of CHP_{exp} (Case Study 2)

Unit (<i>l</i>)	m_l (tonnes)	FF_M	CF	c_l	$(Q_r)_l$ (kJ/mol)	$(CHP_{exp})_l$
Reactor	0.256	1	1	150	1799	307,000,000,000
					CHP_{exp}	307,000,000,000

References

- Bruneau, M., Reinhorn, A., 2007. Exploring the concept of seismic resilience for acute care facilities. *Earthq. Spectra* 23 (1), 41–62.
- Castillo-Borja, F., et al., 2017. A resilience index for process safety analysis. *J. Loss Prev. Process. Ind.* 50, 184–189.
- CCPS, C., 2022. Guidelines for Hazard Evaluation Procedures. Wiley-Blackwell, Chichester.

- Chen, C., et al., 2023. Resilience Assessment and Management: A Review on Contributions on Process Safety and Environmental Protection, vol. 170. Process Safety and Environmental Protection, pp. 1039–1051.
- Cozzani, V., Tugnoli, A., Salzano, E., 2007. Prevention of domino effect: from active and passive strategies to inherently safer design. *J. Hazard Mater.* 139 (2), 209–219.
- Crowl, D.A., Louvar, J.F., 2001. *Chemical Process Safety: Fundamentals with Applications*. s. L. Pearson Education.
- Darbra, R., Palacios, A., Casal, J., 2010. Domino effect in chemical accidents: main features and accident sequences. *J. Hazard Mater.* 183 (1), 565–573.
- Demichela, M., Gallo, M., Salzano, E., 2015. A review of the methodologies for the resilience assessment in the process industry. *Journal of Polish Safety and Reliability Association* 6.
- Dimitriadis, V., Pistikopoulos, E., 1995. Flexibility analysis of dynamic systems. *Ind. Eng. Chem. Res.* 34 (12), 4451–4462.
- Dinh, L., Pasman, H., Gao, X., Mannan, M., 2012. Resilience engineering of industrial processes: principles and contributing factors. *J. Loss Prev. Process. Ind.* 25 (2), 233–241.
- El-Halwagi, M., et al., 2020. Disaster-resilient design of manufacturing facilities through process integration: principal strategies, perspectives, and research challenges. *Frontiers in Sustainability* 1.
- Francis, R., Bekera, B., 2014. A Metric and Frameworks for Resilience Analysis of Engineered and Infrastructure Systems, vol. 121. Reliability Engineering & System Safety, pp. 90–103.
- Ghoroi, C., Shah, J., Thakar, D., Baheti, S., 2021. Process Design and Economics of Production of P-Aminophenol, ume 2110, 15750. *arXiv preprint arXiv*.
- Gill, A., Kadziński, A., 2012. The concept of identification of layers of safety system models through classification of risk reduction measures. *Journal of KONES* 19 (1), 105–115, 19.
- Hewitt, G., Collier, J., 2018. *Introduction to Nuclear Power*. Boca Raton. s.L.:Chapman and Hall/CRC.
- Hollnagel, E., 2013. Resilience engineering and the built environment. *Build. Res. Inf.* 4 (12), 129–139.
- Hollnagel, E., Nemeth, C.P., Sidney, D., 2008. *Resilience Engineering Perspectives: Remaining Sensitive to the Possibility of Failure*. s.L. Ashgate Publishing, Ltd.
- Hoseyni, S.M., Francesco, D.M., Zio, E., 2019. Condition-based Probabilistic Safety Assessment for Maintenance Decision Making Regarding a Nuclear Power Plant Steam Generator Undergoing Multiple Degradation Mechanisms, vol. 191. Reliability Engineering & System Safety, 106583.
- Hoseyni, S.M., Maio, F.D., Zio, E., 2021. Optimal sensor positioning on pressurized equipment based on Value of Information. *Proc. Inst. Mech. Eng. O J. Risk Reliab.* 235 (4), 533–544.
- Hoseyni, S.M., Maio, F.D., Zio, E., 2023. Subset simulation for optimal sensors positioning based on value of information. *Proc. Inst. Mech. Eng. O J. Risk Reliab.* 237 (5), 897–909.
- Hoseyni, S.M., et al., 2014. Effects of soil-structure interaction on fragility and seismic risk; a case study of power plant containment. *Journal of Loss Prevention in the Process Industries* 32, 276–285.
- Huber, G., Gomes, J., de Carvalho, P., 2012. A program to support the construction and evaluation of resilience indicators. *Work* 41, 2810–2816.
- IAEA, 1996. *Manual for the Classification and Prioritization of Risks Due to Major Accidents in Process and Related Industries*. International Atomic Energy Agency, Vienna.
- Jain, P., Mentzer, R., Mannan, M., 2018a. Resilience metrics for improved process-risk decision making: survey, analysis and application. *Saf. Sci.* 108, 13–28.
- Jain, P., et al., 2018b. Process Resilience Analysis Framework (PRAF): a systems approach for improved risk and safety management. *J. Loss Prev. Process. Ind.* 53, 61–73.
- Kang, R., Ale, S., Paté-Cornell, M.E., 2017. A Review of Modeling Approaches for Quantifying Resilience in Engineered Systems, vol. 167. Reliability Engineering & System Safety, pp. 52–65.
- KBA, 2022. *Key Biodiversity Areas Proposal Process: Guidance on Proposing, Reviewing, Nominating and Confirming sites*. Version 1.1. Prepared by the KBA Secretariat and KBA Committee of the KBA Partnership. Cambridge, UK. [online] Available at: <https://www.keybiodiversityareas.org/>.
- Munoz, A., Dunbar, M., 2015. On the quantification of operational supply chain resilience. *Int. J. Prod. Res.* 53 (22), 6736–6751.
- NDA, 2011. *NDA Prioritisation – Calculation of Safety and Environmental Detriment Scores*, s.L. Nuclear Decommissioning Authority.
- Oh, J., 2008. *Methods For Comparative Assessment of Active and Passive Safety Systems with Respect to Reliability, Uncertainty, Economy, and Flexibility*, s.L. Doctoral dissertation, Massachusetts Institute of Technology.
- Øien, K., Massaiu, S., Tinmannsvik, R., Størseth, F., 2010. Development of Early Warning Indicators Based on Resilience Engineering. Institute for Energy Technology, pp. 1–10.
- Parliament, E., 2021. Impacts of the COVID-19 Pandemic on EU Industries. European Parliament, Luxembourg.
- Pasman, H., Kottawar, K., Jain, P., 2020. Resilience of process plant: what, why, and how resilience can improve safety and sustainability. *Sustainability* 12 (15), 6152.
- Poulin, C., Kane, M.B., 2021. Infrastructure Resilience Curves: Performance Measures and Summary Metrics, vol. 216. Reliability Engineering & System Safety, 107926.
- Pourgol-Mohammad, M., Hoseyni, S., Hoseyni, S., Sepanloo, K., 2016. A practical sensitivity analysis method for ranking sources of uncertainty in thermal-hydraulics applications. *Nucl. Eng. Des.* 305, 400–410.
- Provan, D.J., Woods, D.D., Dekker, S.W., Rae, A.J., 2020. Safety II Professionals: How Resilience Engineering Can Transform Safety Practice, vol. 195. Reliability Engineering & System Safety, 106740.
- Righi, A.W., Saurin, T.A., Wachs, P., 2015. A Systematic Literature Review of Resilience Engineering: Research Areas and a Research Agenda Proposal, vol. 141. Reliability Engineering & System Safety, pp. 142–152.
- Scattergood, M., et al., 2020. Process Design and Economics of Production of Ammonia and Urea. University of Sheffield, Sheffield.
- Sengupta, D., Yelvington, P., 2020. Modular intensified processes promote resilient manufacturing. *Chem. Eng. Prog.* 25.
- Sheffi, Y., Rice, J., 2005. A supply chain view of the resilient enterprise. *MIT Sloan Manag. Rev.* 47.
- Shirali, G.H.A., et al., 2012. Assessing resilience engineering based on safety culture and managerial factors. *Process Saf. Prog.* 31 (1), 17–18.
- Sinnott, R., 2005. Chemical engineering design. *Chem. Eng.* 6. Elsevier.
- Taleb-Berrouane, M., Khan, F., 2019. Dynamic Resilience Modelling of Process Systems, vol. 77. CHEMICAL ENGINEERING TRANSACTIONS, pp. 313–318.
- Tian, Y., Pistikopoulos, E.N., 2018. Synthesis of operable process intensification systems—steady-state design with safety and operability considerations. *Ind. Eng. Chem. Res.* 58 (15), 6049–6068.
- Yarveisy, R., Gao, C., Khan, a.F., 2020. A Simple yet Robust Resilience Assessment Metrics, vol. 197. Reliability Engineering & System Safety, 106810.
- Yodo, N., Wang, P., 2016. Engineering resilience quantification and system design implications: a literature survey. *J. Mech. Des.* 138 (11), 1–13.
- Yousefpour, F., et al., 2017. Creep rupture assessment for Level-2 PSA of a 2-loop PWR: accounting for phenomenological uncertainties. *Nucl. Sci. Tech.* 28 (8), 1–9.
- Zhang, Y., Liang, X., Reniers, G., 2019. Integrating chemical hazard potential and exposure risk for safety assessment in chemical industry parks. *J. Loss Prev. Process. Ind.* 60, 169–181.