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Contents

1. Executive summary

We witness many severe accidents in different sectors worldwide every year, resulting in fatalities, injuries, environmental pollution, property loss, etc. Safety management aims to use interventions to prevent these undesired events and thus avoid different kinds of loss. Various interventions that have different safety performances and costs are available for managers; one safety intervention may have multiple functions, such as avoiding fatalities and protecting the environment. As a result, we need to know the value of safety when deciding on investment in interventions. To support decision-making on safety management, the Safety & Security Science Group in Delft University of Technology (TUD) conducted a project on the value of safety to get insight into the values considered in the context of safety. Four research questions have been answered, as follows:

1.1. What are the values of safety?

According to the literature review and questionnaire survey, safety has multiple values, including health value, environmental value, economic value, sustainability value, ethics value, resilience value, political value, and reputation value. Safety values may change with different countries, organisations, sectors, and stakeholders. Different countries consider the value of safety differently. Generally speaking, health value gains the most attention, followed by economic value and environmental value. A hierarchy of safety values was developed, reflecting this, as shown in Figure 1.

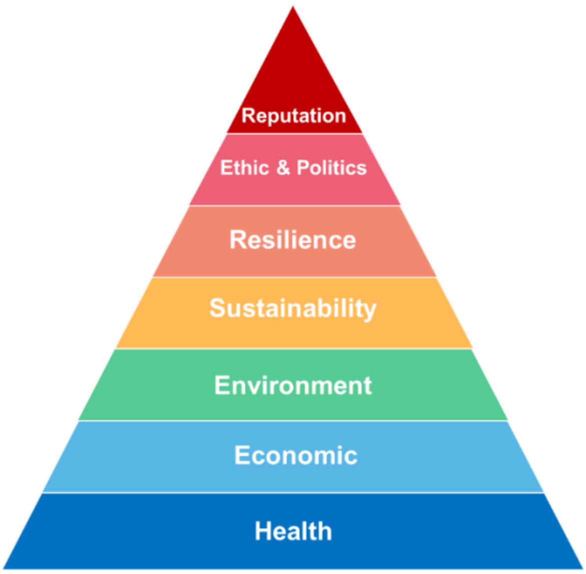

Figure 1: Hierarchy of safety values

1.2. What methods are used to measure the value of safety?

To determine the performance of safety measures and the investment in safety interventions, it is necessary to measure the value of safety. Our investigation identified 37 approaches to this measurement. The most frequent approach is quantitative risk assessment (QRA), followed by Bayesian network, fuzzy theory, and cost-benefit analysis. Different tools may be used for quantifying different safety values. For example, risk indexes are always used to measure the environmental value.

1.3. What are the limitations of past research?

Although eight values are obtained from the literature, most of this research focuses on the health value of safety, environmental value, and economic value; other values currently lack research. There is a lack of approaches for measuring sustainability value, ethics value, resilience value, political value, and reputation value. In light of the health value, most research considers physical health (e.g., fatalities and injuries and diseases) while only a few papers focus on investigating mental health, and no assessment approaches for mental health analysis before accidents are available in the literature. The monetisation of consequences is a critical step in economic value analysis, and the lack of economic data for economic calculation is an obstacle for economic value.

1.4. What gaps have been identified?

A workshop was held on 23 September 2021 to collect reflections from professionals from diverse sectors on the primary findings from the literature review and questionnaire survey. Several gaps have been identified according to the discussions of this workshop. The main gaps are i) Some social values are almost not picked up in the literature under the safety domain, such as freedom, respect, community, and responsibility. The association of those social values with safety and the necessity of involving more social values as a part of safety values need further investigation. ii) Different terminology and definitions associated with safety values are used globally and within organisations. Therefore, safety and associated values are understood and applied in another way. The achievement of taxonomy and consensus is essential but challenging.

1.5. What is the roadmap for future safety management?

Using the results of this study, we develop a value-based safety management framework for improving safety management in the future. Value-based safety management consists of four steps: define sociotechnical systems, identify values of safety, measure values of safety, manage values of safety via design and operation. The four steps constitute life-cycle safety management that can dynamically adjust safety interventions to ensure the safety of sociotechnical systems in their entire life cycles.

2. Introduction

Safety may be considered a condition related to the absence of accidents, losses, etc. (Leveson, 2004). Furthermore, safety can also be thought of as the antonym of risk, where "safe" can be considered a condition or situation characterised by an acceptable risk (Aven, 2014). In addition, Hollnagel (2014) defines safety (Safety-II) as the ability to succeed by performance variability and adaptation under expected and unexpected conditions.

Safety management, therefore, aims to prevent or minimise harm to individuals, property, and the environment. In this framework the purpose of safety science is to maximise the probability of intended and acceptable outcomes. For example, there are many risk reduction strategies in the chemical industry, including inherent safety, passive barriers, active barriers, emergency procedural barriers, a culture of safety, and specific safety education that have been developed over time (Chen et al., 2020; Khan and Amyotte, 2003; Reniers et al., 2011).

However, while implementing safety processes can be highly effective at reducing the occurrence and impact of harm such interventions are not without cost. As an investment in safety will inevitably reduce investment in other activities (Chen et al., 2021a; Reniers and Van Erp, 2016), it is therefore important that interventions are carefully targeted to deliver the maximal return on investment. Stakeholders must therefore be aware of both the values of any proposed safety interventions and the values that they expect to obtain from implementation before starting a safety management process. To support such a decision-making process we performed a literature review and surveyed domain experts to identify impactful recommendations.

2.1. Aims and objectives

Here we aim to develop insight into how the understanding and value of safety may differ between sectors and counties and describe the differing approaches for measuring these values and their associated limitations. Using this information, we aim to develop a hierarchy for safety interventions couple with a roadmap to ensure successful delivery.

3. Research methodology

Briefly, the study consisted of two distinct phases. First, we identified safety values and measurement approaches using a literature review. Second, we validated these safety values by surveying domain experts. For detailed methods please see (Appendix A).

4. Results

4.1. Literature review results

4.1.1. Value identified from keywords

To study safety values, we analysed the keywords of the publications related to the value of safety using the co-occurrence analysis function of VOSviewer. A total of 7,699 keywords set by authors were identified by VOSviewer. Among these words, only 267 keywords occur at least five times, with 1,253 keywords occurring twice. The most frequent keyword was risk assessment (323), followed by risk management (136), risk analysis (111), risk perception (87). To identify possible values in the safety domain, we further excluded the keywords unrelated to safety values. Per Table 1, seven distinct values were identified. Health values were the most frequently found values, which included general health, mental health, occupational health, and public health. Environmental-related values were the second most frequently found, and consisted of air pollution, water pollution, radiation pollution, and general environmental values.

Table 1: Safety values identified from keywords

Values	Occurrences
Health	283
Environmental	142
Economic	70
Ethics	67
Sustainability	46
Reputation	17
Resilience	15

4.1.2. Values identified from titles and abstracts

Besides keywords, important safety values may also exist in the abstract and title of papers. As a result, we analysed the terms present in publication titles and abstracts using the text data analysis function of VOSviewer. A total of 589,52 terms were obtained from 3,685 papers; 1,389 terms occurred more than 10 times. The most frequent term was risk (1,225), followed by study (1,132), paper (1,042), model (877), analysis (872), and risk analysis (851). We further refined the process to highlight specific safety values by excluding the terms irrelevant to values of safety.

With this process we were able to identify eight distinct terms, the seven described above with the addition of "political". As above health and environmental were the two most commonly identified terms, as shown in Table 2.

Table 2: Values identified from titles and abstracts.

Values	Occurrences
Health	886
Environmental	499
Economic	469
Sustainability	126
Resilience	58
Ethics	43
Political	29
Reputation	17

4.1.3. Safety value analysis

4.1.3.1. Health

The health value refers to the physical health and mental health of employees and the public. Consequently, occupational health is the primary concern for the health value (Champoux and Brun, 2003; Hohnen and Hasle, 2011; Robson et al., 2012). Importantly, in 2018 the International Organisation for Standardisation (ISO) published ISO 45001 for management systems of occupational health and safety (OH&S), substituting OHSAS 18001 (Darabont et al., 2017). The objective of ISO 45001 is to reduce occupational injuries and diseases, promoting and protecting physical and mental health. In terms of mental health, the work mainly focuses on the mental health of frontline workers, healthcare workers, government leaders, and the public after an accident (Kovacevic et al., 2020; Loganovsky et al., 2008; Shigemura, 2021).

4.1.3.2. Environmental

Environmental issues in the safety domain are typically related to pollutants caused by accidents, such as the release of hazardous materials into the local environment. For example, Duarte et al. (2012) studied the ecological risk caused by oil spills occurring during maritime transportation in the coastal tropical area of North-eastern Brazil. Mrozowska (2021) conducted a risk assessment for major accidents offshore during drilling and production operations based on the provisions of Directive 2013/30/EU, considering the impacts on the marine ecosystem. Moreover, emergency response actions to mitigate damage may themselves cause further harm if not implemented correctly, as such they also need to be addressed as part of this value.

4.1.3.3. Economic

Economic value mainly concerns the costs of accidents, the costs of safety interventions, and the expected benefits from safety intervention (Chen et al., 2021a; Reniers and Van Erp, 2016). Ahn et al. (2021) developed a cost assessment model for sustainable health and safety management of high-rise residential buildings. Yang and Maresova (2020) investigated the impact of occupational health and safety management standards on the financial performance of pharmaceutical firms in China. Importantly, Elvik (2019) demonstrated that the monetary valuation of road safety is very imprecise, which may lead to difficulties in applying cost-benefit analysis to decision-making on road safety measures.

4.1.3.4. Sustainability

Safety is a precondition for sustainable development, as such frequent or high impact accidents limit the sustainability of an industry (Chen et al., 2021a). For instance, several chemical manufacturers in China were forced to close by the government in response to frequent safety breaches (Chen and Reniers, 2020; Yang et al., 2020). Another well-known example is the planned shutdown of all nuclear power plants in Germany by 2023, a process started in response to the Fukushima nuclear disaster in 2011 (Bruninx et al., 2013). Alongside industry, safety risks are also related to the sustainability of cities. Zhang et al. (2019) studied the relationship between fire safety management and the sustainability of urbanisation while (Wu et al., 2018) developed a risk assessment approach for fire disasters in subway stations for the sustainability of underground facilities.

4.1.3.5. Resilience

Resilience may refer to the ability of a system to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions (Chen et al., 2021b; Linkov et al., 2018). Improving the safety of a system can enhance its resilience of the system. Ewertowski and Butlewski (2021) developed a pandemic residual risk assessment tool for enhancing organisational resilience within Polish companies. Bragatto et al. (2021) studied the major accident management in Italian Seveso industries under the impact of the COVID-19 pandemic to improve organisational resilience.

4.1.3.6. Ethics

Ethical values in the safety domain mainly consist of fairness, justice, and trust in risk management. Begg (2018) researched the local stakeholder participation in European flood risk management. Thaler et al. (2020) explored compensation processes arising from for spatial flood risk management by comparing the approaches used in Austrian and Dutch. Mah et al. (2014) investigated the effects of risk perception, trust, and public engagement in nuclear decision-making in Hong Kong.

4.1.3.7. Political

Some significant accidents, such as nuclear accidents, may impact safety policies or politics (Constantinescu and Bugoi, 2007). Besides, the cost of risk reduction interventions can affect the financial status and other investments of a country (Elvik, 2001; Kenny, 2012). Similarly, risk perception is influenced by psychological, social, physical, political (here regulatory and normative), and cultural factors (Tancogne-Dejean and Laclémence, 2016).

4.1.3.8. Reputation

A system such as a company has many stakeholders such as customers, employees, and suppliers. Their interactions with these stakeholders are strongly influenced by their reputation, a poor safety record can be a significant negative driver of reputation, impacting the company’s ability to do business (Kamiya et al., 2021). Tundjungsari and Yugaswara (2015) developed an approach to promote emergency response collaboration considering the effects of cooperation on reputation. Kamiya et al. (2021) studied the impact of cyberattacks on the reputation of target companies. They found out that successful attacks with personal financial information loss harm reputation.

4.1.4. Values identified from different sectors

We investigated the occurrence of the eight previously identified values within the literature of specific sectors, as summarised in Table 3. Interestingly both the health and environmental values were present in all seven sectors assessed further confirming the importance of these values. Of the sectors assessed the construction and mining industry had the most diverse range of literature, with five values being identified for each. Surprisingly, given the public and risk profile of the oil and gas industry we were only able to identify literature relating to two of the eight fields.

4.1.1. Values identified from different countries

We then repeated this drilldown however this time focusing on 14 countries rather than sectors, with results shown in Table 4.

We demonstrated that all 14 countries pay attention to four values: health, environmental, economic, and ethics. Interestingly the political value was only identified for three of the assessed counties, Brazil, South Africa, and Turkey. Furthermore, it is of interest that we were unable to identify literature relating to sustainability for either Canada or Norway considering their global reputation compared to some of the other investigated countries

Table 3: safety values in different sectors (3,685 papers).

Sectors	Safety values							
	Health	Environmental	Economic	Sustainability	Ethics	Resilience	Political	Reputation
Chemical								
Construction								
Healthcare								
Maritime								
Oil and gas								
Mining								
Utilities								

Table 4: safety values in different countries (3,685 papers).

Countries	Safety values							
	Health	Environmental	Economic	Sustainability	Ethics	Resilience	Political	Reputation
Australia (206)								
Brazil (57)								
Canada (227)								
China (1,116)								
England (364)								
India (118)								
Italy (127)								
Japan (131)								
Netherlands (155)								
Norway (30)								
South Africa (88)								
Turkey (85)								
USA (131)								

4.2. Method identification results

Here we attempted to identify the methodology used in publications.

4.2.1. Methods identified from keywords

According to keyword analysis, 37 methods/approaches were identified, as shown in Table 5. The most frequent approach is quantitative risk assessment (QRA) (58), followed by Bayesian network (46), GIS (Geographic Information System) (45), fuzzy theory (37), and cost-benefit analysis (33). The identified methods/approaches are described in Appendix C - Method analysis.

Table 5: Occurrences of methods/approaches identified from keywords

Methods	Occurrences
QRA (quantitative risk assessment)	58
Bayesian network	46
GIS (Geographic Information System)	45
Fuzzy theory	37
Cost-benefit analysis	33
AHP (Analytic Hierarchy Process)	29
Probabilistic risk assessment	22
Cost-effectiveness analysis	18
CFD (Computational Fluid Dynamics)	13
Monte Carlo method	13
Event tree	12
Artificial neural network	10
Questionnaire	10
FDS (Fire Dynamics Simulator)	9
Index method	8
Machine learning	8
Economic analysis	7
Game theory	7
Analytical method	6
Willingness to pay	6
Multi-criteria decision-making methods	5
Value of statistical life	5
Genetic algorithm	4
Petri-net	4
HAZOP	3
Risk matrix	3
Big data	2
Bow-tie model	2
FEM (Finite element analysis)	2
G1 method	2
Graph theory	2
Human capital method	2
Information diffusion theory	2
Interview	2
Prospect theory	2
QALY (Quality-adjusted life-year)	2
Risk index	2

4.2.2. Methods identified from titles and abstracts

According to the text data analysis function of VOSviewer, we identified 19 methods from the titles and abstracts of the literature, as shown in Table 6. The most frequent method was questionnaire (139), followed by QRA (quantitative risk assessment), interview, matrix, and Bayesian network.

Table 6: Occurrences of methods identified from titles and abstracts

Methods	Occurrences
Questionnaire	139
QRA (quantitative risk assessment)	134
Interview	94
Matrix	58
Bayesian network	56
Risk index	51
Cost-effectiveness analysis	50
Cost-benefit analysis	46
Probabilistic risk assessment	44
Fuzzy theory	36
CFD (Computational Fluid Dynamics)	28
Fault tree	28
Event tree	24
FDS (Fire Dynamics Simulator)	19
Cost-benefit analysis	16
QALY (Quality-adjusted life-year)	13
Economic evaluation	12
Principal component analysis	12
Human capital method	10

4.3. Questionnaire results

Below we present the findings from 13 interviews with safety professionals, from different industry sectors and counties, in an attempt to validate the results obtained from the literature review. Three categories of questions were constructed to achieve this goal:

1. Definition of safety;
2. Categories of the value of safety;
3. Measuring the value of safety.

The questionnaire can be found in Appendix D.

4.3.1. Definition of safety

(1) Personal perspective

As shown in Figure 2, the two definitions of safety from the respondents personal perspective were;

"a condition or judgment of acceptable control over negative consequences caused either deliberately or by accident"

and,

"safety as a physical state with relative freedom from hazards, injuries, or loss of personnel and property"

This result demonstrates that respondents mainly considered safety as a physical state, condition, or a judgment with relative freedom from damages caused deliberately or by accident. Thus, safety management is used to prevent or minimise the losses from accidents and maintain or improve the safety state.

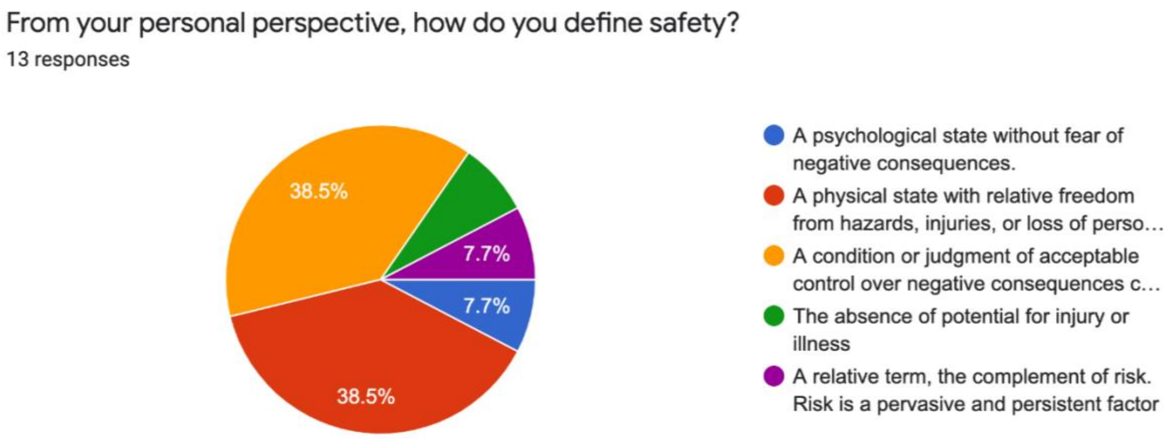

Figure 2: Definitions of safety from the personal perspectives.

(2) Organisations' perspective

We then asked the respondents how their respective organisations would define safety, as shown in Figure 3.

Here by far the predominant answer defined safety as;

"a condition or judgment of acceptable control over negative consequences caused either deliberately or by accident"

This result is roughly consistent with the results from a personal perspective. Safety is mainly associated with the freedom from negative consequences or damage caused by accidents and deliberate actions.

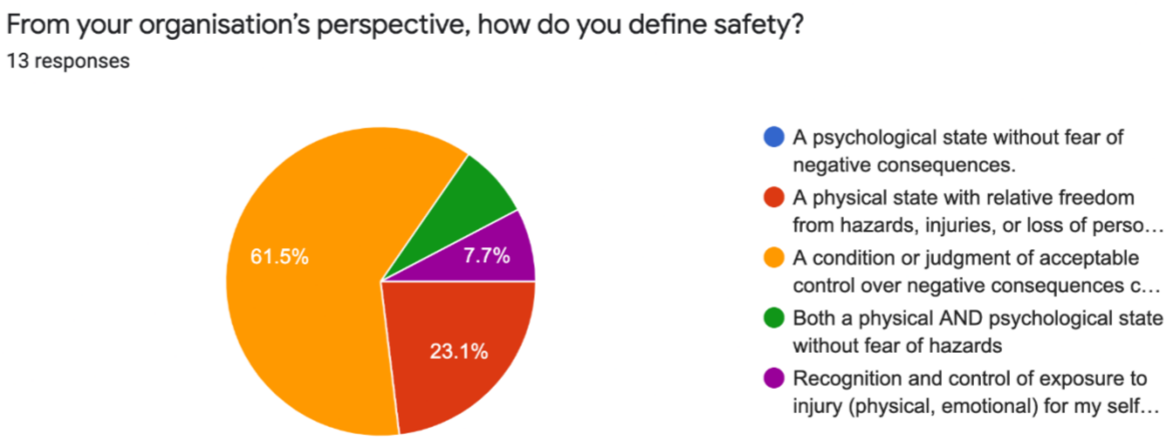

Figure 3: Definitions of safety from the organisations' perspectives.

4.3.2. Categories of the value of safety

(1) Association towards safety

When asked to describe safety respondents identified several key terms which are shown in Table 7. The most frequently identified were "*health and life*", "*environment*", and "*economic*", which tallies with the results found during the literature review.

Table 7: Terms associated with safety values

Terms	Occurrences
Health and life	92%
Environmental	85%
Economic	85%
Reputation	69%
Ethics	62%
Sustainability	62%
Resilience	62%

(2) Ranking

We then asked respondents to rank five of these values based on their importance in preventing negative consequences with results shown in Figure 4. Once again "*health and life*" was the most highly ranked with almost all respondents rating it most highly.

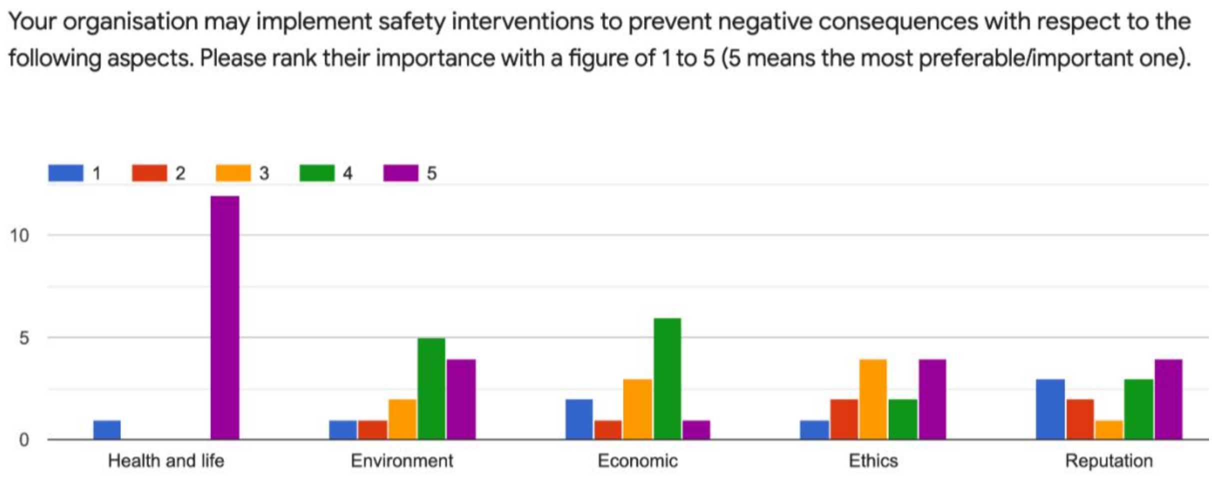

Figure 4: Ranking the values associated with safety

We also asked respondents to add and rank any additional values that they thought should be included, with results shown in Table 8. Trust was the most frequent answer and also the most highly ranked.

Table 8: Additional terms and ranking

Terms	Mentions	Rank
Fire safety	4	2
Personal security	4	2
Resilience/Personal balance	4	2
Value to wellbeing	1	2
Science/Data	1	2
Trust	5	1

4.3.3. Measuring the value of safety

(1) Organisations' approach/method

In terms of the approaches used by the respondent's organisation, the majority of respondents emphasised that their organisation used both qualitative and quantitative approaches, as shown in Figure 5.

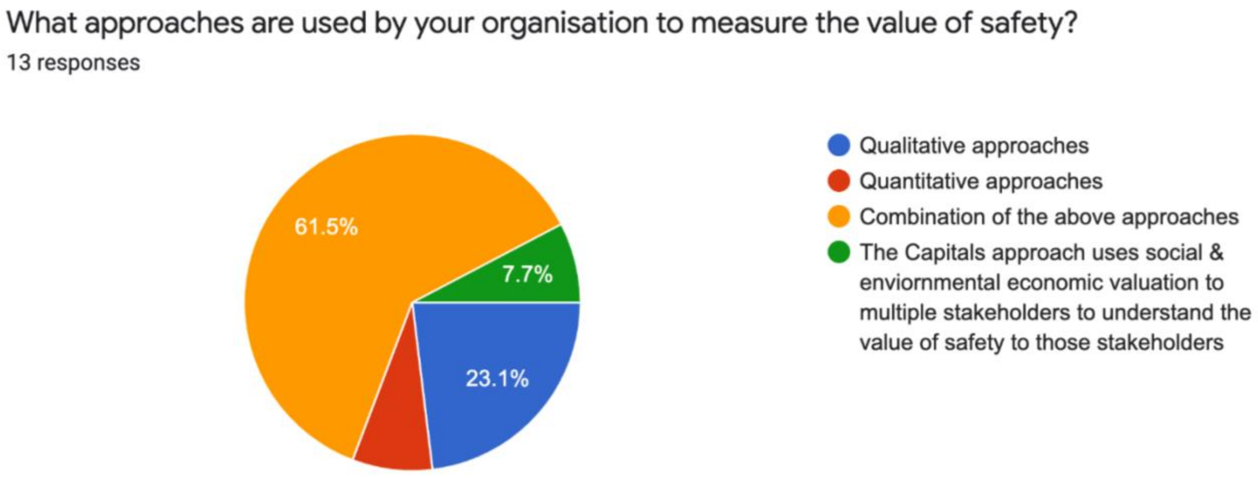

Figure 5: Approaches that are used by organisations to measure the value of safety.

(2) Sector's approach/method

From the sector perspective, we have asked the respondents as to what approach or method do they think their industry sector commonly uses to measure the value of safety, a similar picture emerges where a mixed approach was by far the most common response. The approaches or methods used in different sectors to measure the value of safety are detailed in Table 9.

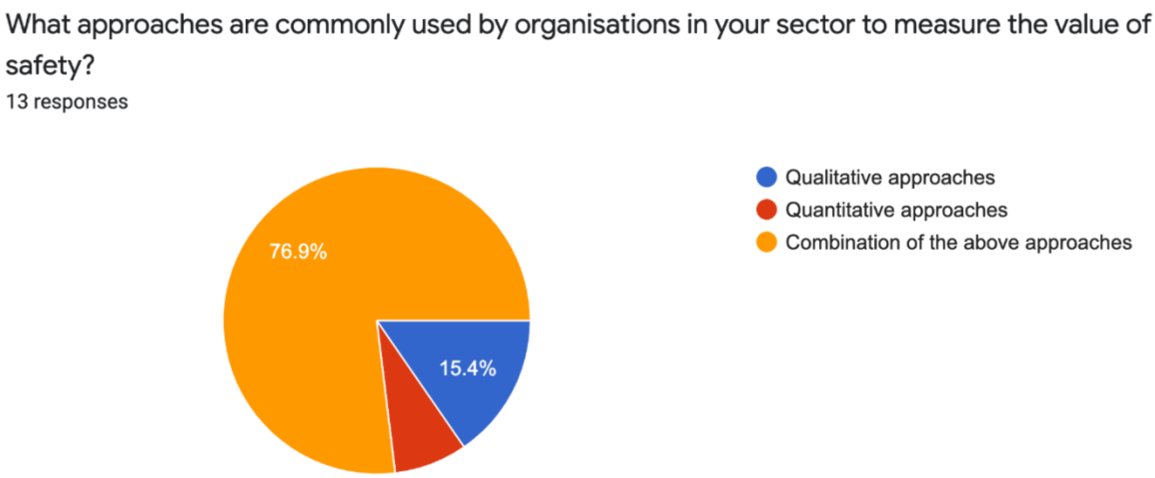

Figure 6: Approaches/methods that are commonly used in respondents' sectors to measure the value of safety.

Table 9: Approaches/methods commonly used in respondents' sectors to measure the value of safety

Sectors of the respondents	Approaches/methods commonly used
Construction	Qualitative approaches
Chemical	Combination of qualitative approaches and quantitative approaches
Oil & gas	Combination of qualitative approaches and quantitative approaches
Manufacturing	Combination of qualitative approaches and quantitative approaches

(3) Approaches to measure values of safety

We also asked the respondents when it comes to approaches for measuring values of safety. For the questionnaire and risk-assessment approaches, the "*health and life"* value was the most common, whereas for the index-based approach the "*reputation"* value was the most highly rated.

Some additional remarks from the respondents are that environmental value is also assessed in a similar way where economic and health & life garnered the highest spot.

5. Discussion

5.1. Research gaps

Per the literature review safety values can be classified into eight categories. Similarly, the 37 methods or approaches were divided into eight categories and linked with the safety values as shown in Table 10. This process allowed us to define the following research gaps:

1. Although eight values are obtained from the literature, most of these papers focus on the health, environmental, and economic values, while there was a distinct lack of research into the other values. Also, the majority of papers only discuss a single value with very few addressing multiple.
2. A total of 37 methods of approaches were identified in the literature related to the value of safety, however most were used to investigate the health and economic values with the others underrepresented.
3. For the health value most research only considers physical health (e.g., fatalities and injuries and diseases) caused by accidents. There is little assessment of the impact on mental health of accidents, or the role of mental health in preventing accidents.
4. For the environmental value, the majority of work is focused on the impact on pollution resulting from accidents, studies frequently lack a full description of the impact on ecosystems, residents and their livelihoods.

5. When discussing the economic value, the most critical work is to quantify the economic impact of an accident to allow for accurate reporting. The monetisation of consequences is a critical step in the analysis of economic impacts and the generating a full understanding of the economic value to all stakeholders.
6. For the resilience and sustainability values in the safety domain, most papers lack quantification of the impact of safety in their calculation.
7. The ethics value in the safety domain relates to perceived fairness, justice, and trust. However, only a few papers pay attention to ethical values related to safety.
8. Political values were only assessed in a few counties, more diverse studies are therefore needed to identify country level or regional trends.

Table 10 A characterisation of approaches for safety values.

Categories	Approaches	Safety values							
		Health	Environmental	Economic	Sustainability	Ethic	resilience	Political	Reputation
Hazard identification	Hazop								
Risk assessment methods	QRA (quantitative risk assessment)								
	Bayesian network								
	Risk index								
	Probabilistic risk assessment								
	Risk matrix								
	Event tree								
	Analytical method								
	Graph theory								
	Petri-net								
	Bow-tie model								
	Monte Carlo method								
Economic methods	Cost-benefit analysis								
	Cost-effectiveness analysis								
	Economic analysis								
	Game theory								
	Prospect theory								
	Willingness to pay								
	Human capital method								
	QALY (Quality-adjusted life-year)								
	Value of statistical life								
Multi-criteria	AHP (Analytic Hierarchy								

decision-making methods	Process)								
	Index method								
	G1 method								
	Multi-criteria decision-making methods								
Survey methods	Interview								
	Questionnaire								
Data-driven methods	Genetic algorithm								
	Machine learning								
	Artificial neural network								
	Big data								
Fuzzy methods	Fuzzy theory								
	Information diffusion theory								
Auxiliary software	FEM (Finite element analysis)								
	CFD (Computational Fluid Dynamics)								
	FDS (Fire Dynamics Simulator)								
	GIS (Geographic Information System)								

5.2. Workshop discussion results

In order to obtain reflections on the primary findings from the literature review and questionnaire survey, a workshop was held on 23 September 2021 to collect feedback from professionals from diverse sectors. Those participants were asked to give reflections on the primary findings of the literature review study and the identified research gaps. The discussion results from this workshop are as follows:

1. Safety values may be different in different countries and industries, and safety values can change over time due to the development of society. For instance, issues with chemical waste and pollution are becoming more important as societies develop and out global understanding of risk develops. Taken together these differences show the need for the thinking around safety to evolve and not just be a single static intervention.
2. Currently, the health, environmental and economic values are the most widely studied. However the assessment of mental health represents a significant gap. Measuring mental health is a challenge that needs to be addressed in the future.
3. Some social values are almost entirely missing from the safety related literature, such as freedom, respect, community, and responsibility. The association of those social values with safety and the necessity of involving more social values as a part of safety values need further investigation.
4. There are a lack of approaches for measuring certain values (such as sustainability, ethics, resilience, political, and reputation). To facilitate the measurement of those values, several aspects may help:
    - When thinking about the value of safety, it’s essential to consider the question of ‘value to who?’. A stakeholder mapping is necessary for measuring safety and associated values.
    - Different terminology and definitions associated with safety values are used globally and within organisations. Therefore, safety and associated values are understood and applied in differing ways. The achievement of taxonomy and consensus is important but challenging.
5. Several requirements for valuation methods are suggested:
    - Values should not be considered in isolation.
    - Valuation methods should enable the integration of different values. For instance, the impact of pollution is mainly seen as an environmental issue, but this also has an impact on human health.
    - Valuation methods should be broad and enable us to think beyond ‘safety’ and to a broader range of benefits (e.g., cost, productivity, wellbeing, safety).
    - Valuation should use existing frameworks and terminology where possible to integrate safety into existing agendas and narratives.

- Valuation methods should be clear and straightforward, relevant, and appealing to the board room, and designed for practitioners but not academics.
- Valuation methods should be flexible to enable the changing world of work to be considered, e.g., informal sector, remote working

5.3. Hierarchy of safety values

Per the results of the two phases, we generated a hierarchy of seven safety values, as shown in Figure 12. When making health and safety interventions the hierarchy should be followed from top to bottom, with the needs of the lower values being prioritised over those above them. The various methodologies associated with each level of the hierarchy are shown to the right, and stakeholders to the left.

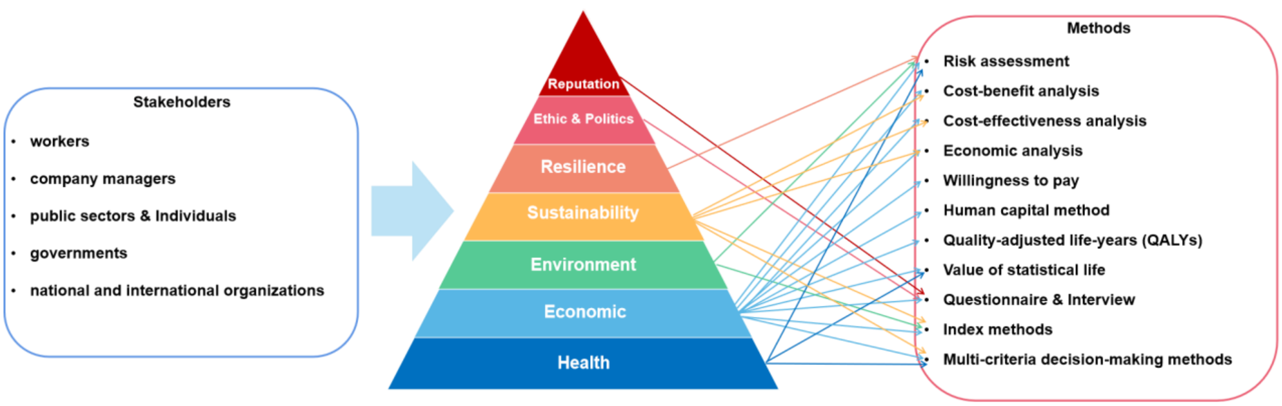

Figure 12: Hierarchy of Safety values.

5.4. Roadmap for value-based safety management

Safety values are of importance in safety management as they are related to the safety requirements of stakeholders. For example, in a sociotechnical system such as a chemical plant, the safety level of the system can be improved by managing the values of safety shown in the hierarchy starting at the bottom and should progress through a defined roadmap, as shown in Figure 13.

The first element is to define sociotechnical systems, i.e., identifying the target of the safety management and characterizing all the elements in the system. For example, the workers, processes, hazards, and any current safety and emergency protocols and the operating environment should be defined along with the interactions between them.

Decision makers should then identify the safety values which need to be addressed and define an acceptable level of safety for each as well as a way of measuring safety outcomes. Targeted interventions should then be made to address safety concerns. Importantly, once implemented the intervention and value should be reassessed to determine if the acceptable safety threshold has been met.

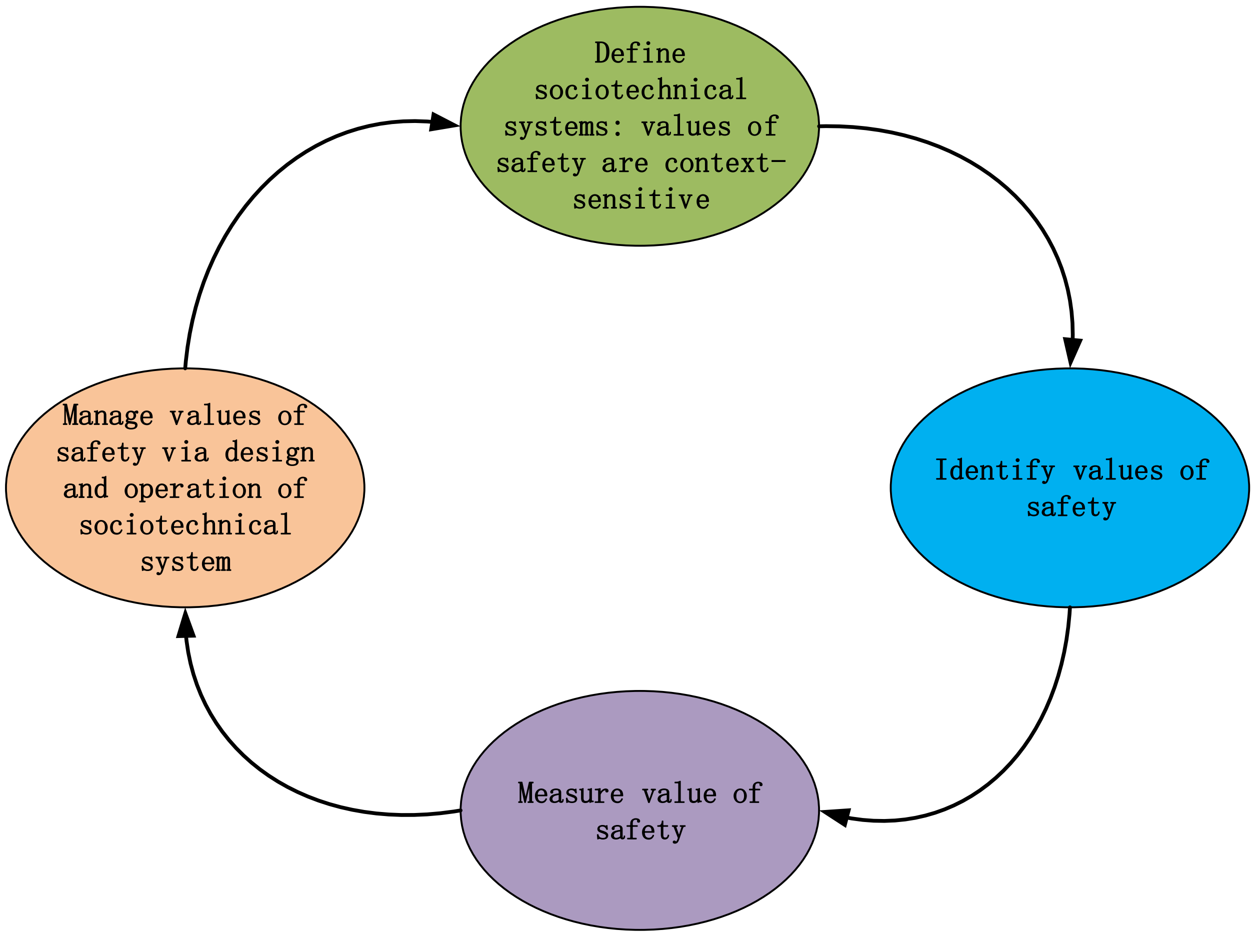

Figure 13: Roadmap of value-based safety management.

6. Conclusions

Using a literature review and interview process we were able to define a clear hierarchy of safety values and the methods that can be used to assess them. Implementing this hierarchy in conjunction with a roadmap for value-based safety management will ensure that safety interventions deliver the maximal return on investment and improve over time to meet evolving needs.

Existing research into the value of safety is limited and typically focuses on health and economic values, there is an important need to investigate other values in more depth and across more industry sectors and regions. However, before undertaking such studies it would be essential to address the relatively limited methodologies that can be used to measure the value of safety, as many valuation criteria are currently poorly articulated and little understood. Importantly we also identified that there is a signification deviation in the usage of terminology at both the sector and national level.

Further studies with improved methodologies coupled with aligned terminology will improve knowledge sharing, the understanding of safety values and importantly allow for improved safety interventions.

7. Recommendations

Based on our findings we suggest the following recommendations for practitioners:

- Integrate the hierarchy of safety values into the development and implementation of safety interventions to deliver maximal value.
- Ensure that social values are become part of the discourse around safety and safety interventions.
- Standardise safety terminology within organisations and globally to allow for better knowledge sharing and integration.
- Implement a value-based safety management framework to maximise impact of safety interventions.

Furthermore, we identified the need for further research to address the following questions:

- Future activities should attempt to address the gaps identified in this report, to improve how safety is currently valued and measured, considering facets such as mental health, sustainability and resilience, etc.
- The valuation methods used to measure safety need to be updated to consider its value from a wider variety of perspectives.

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8. Appendix A - Detailed methods

8.1. Literature review

According to the research objective of this step, a bibliometric analysis is conducted to find out the values of safety. The literature review method with five steps based on bibliometric analysis is shown in Figure A1. As shown in Figure A1, this methodology consists of five steps: searching databases (Web of Science Core Collection) on pre-set keywords, refining literature based on titles and abstracts, bibliometric analysis, identifying safety values, identifying methods/approaches for measuring safety values.

Two levels of pre-set keywords were used to formulate a search statement, and the extensive literature from the online library of the Delft University of Technology was collected in the first step. The bibliometric data were collected on 20 May 2021 from the Web of Science (WoS) Core Collection (which searched Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Art and Humanities Citation Index (A&HI), Conference Proceedings Citation Index-Science (CPCI-S), Conference Proceedings Citation Index-Social Science and Humanities (CPCI-SSH), Book Citation Index-Science (BKCI-S), Book Citation Index-Social Sciences and Humanities (BKCI-SSH), and Emerging Sources Citation Index (ESCI)). The publications in local journals and unpublished academic documents are excluded from the research due to language barriers and unavailable permissions. The timespan is set from 1900-2021. The searching topics used for searching are divided into seven categories: safety, accident, environmental impact, human life, health, economic loss, and social influence. Keywords in different categories are linked as follows: (Safety OR Accident) And (Environmental impacts OR Human life OR Health OR Economic loss OR Social influence). The detailed keywords and search statement can be found in Appendix B - Pre-set keywords and search statement. The search resulted in 7232 bibliographic papers from 3617 journals. Then, the obtained publications are refined by reading the title and abstract of each paper to find out the most relevant papers. Finally, 3685 papers were screened out from 7232 searched papers. The 3685 papers consist of a literature database for the following bibliometric analysis. According to the literature database, a bibliometric analysis based on VOSviewer is conducted to characterise the literature related to the value of safety.

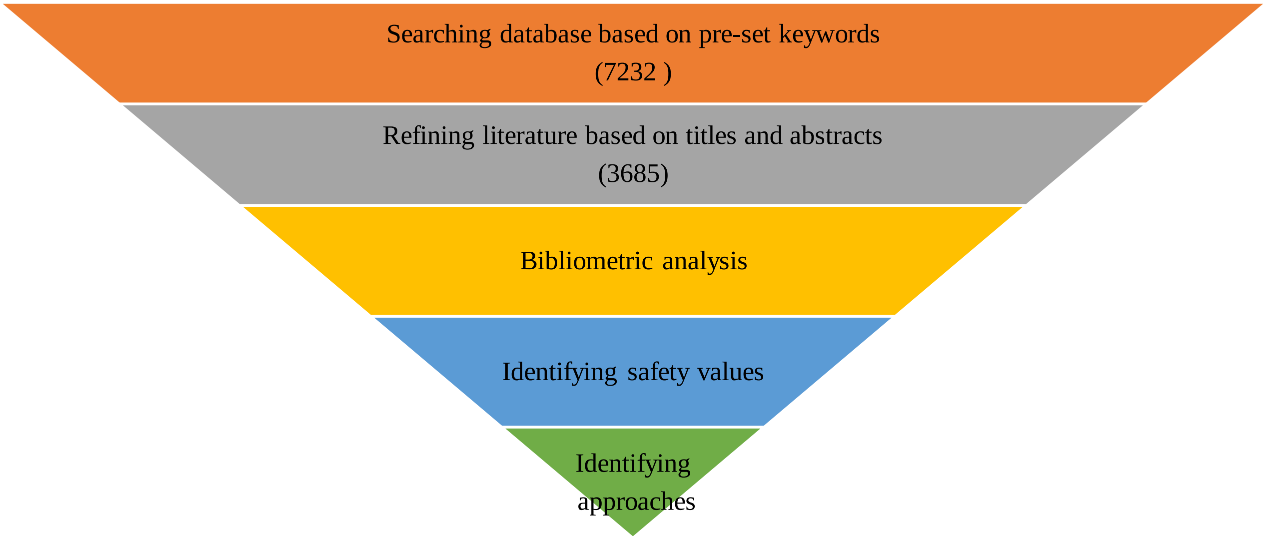

Figure A1: literature review methodology with five steps.

In this research, the bibliometric analysis is based on VOSviewer to characterise the literature related to the value of safety. VOSviewer is widely used in the academic domain to review a research topic De Bakker et al. (2005); (Li et al., 2017; van Nunen et al., 2018; Amin et al., 2019a; Amin et al., 2019b; Zhang et al., 2019a). VOSviewer can generate different kinds of maps based on bibliometric data for visualizing and exploring a large number of literature documents. In a map, items are the objects of interest, such as authors, institutions, publications, and topics. The link between two items in a map represents the connection or relation between two items. As a result, the software can analyse the bibliographic coupling links between publications, co-authorship links between researchers, co-occurrence of topics or keywords, etc. (van Eck and Waltman, 2019).

8.2. Questionnaire survey

In this step, a series of questions are designed to validate the results obtained from the literature review and provide the viewpoints of safety experts on the value of safety. This questionnaire aims to investigate the definition of safety, the categories of safety values and then suggest practical approaches for measuring the value of safety. These questions are divided into three types: (i) definition of safety, (ii) categories of the value of safety, and (iii) measuring the value of safety. The questionnaire is assigned to safety experts in different sectors, and then the questionnaire results are analysed by simple statistical analysis. A total of 13 respondents (safety-related professionals) in various sectors (including construction, chemical, oil & gas, etc.) from typically developed countries and developing countries were involved in this questionnaire survey. This questionnaire can be found in Appendix D - Value of Safety Survey Questions.

8.3. Workshop discussion

According to the results obtained from the literature review and questionnaire survey, the limitations of past research and possible research issues in the future are discussed in Section 5. To get reflections on the obtained preliminary results from the literature review and questionnaire survey, a workshop was held on 23 September 2021. Professionals from academia, the oil & gas sector, the nuclear sector, and the aviation sector were involved to get insight from diverse industry perspectives.

Finally, based on the findings from the literature review and questionnaire survey and the reflections from the workshop, a hierarchy of safety values was proposed with seven-level values. A roadmap on value-based safety management is developed to support decision-making on safety interventions and thus contribute to a safer world. This roadmap is also a framework for future research on the value of safety.

First-level keywords	Second-level keywords	Search statement
Safety	Safety intervention Safety measure Safety barrier Safety culture Safety climate Safety perception Safety training Safety learning Safety function Safety investigation Safety design Safety management Safety monitoring Safety inspection Safety detection Safety legislation Safety investment Safety policy Inherent safety Emergency plan Emergency rescue Emergency response Emergency evacuation Emergency alarm Risk assessment Risk management Risk treatment Risk analysis Risk perception Risk prediction Risk reduction Hazard identification Faults diagnosis Cognitive defect Failure analysis Accident reporting Causal analysis Fire fighting	((“Safety intervention*” OR “Safety measure*” OR “Safety barrier*” OR “Safety culture*” OR “Safety climate*” OR “Safety perception*” OR “Safety training*” OR “Safety learning*” OR “Safety function*” OR “Safety investigation*” OR “Safety design*” OR “Safety management*” OR “Safety monitoring*” OR “Safety inspection*” OR “Safety detection*” OR “Safety legislation*” OR “Safety investment*” OR “Safety policy*” OR “Inherent safety*” OR “Emergency plan*” OR “Emergency rescue*” OR “Emergency response*” OR “Emergency evacuation*” OR “Emergency alarm*” OR “Risk assessment*” OR “Risk management*” OR “Risk treatment*” OR “Risk analysis*” OR “Risk perception*” OR “Risk prediction*” OR “Risk reduction*” OR “Hazard identification*” OR “Faults diagnosis*” OR “Cognitive defect*” OR “Failure analysis*” OR “Accident reporting*” OR “Causal analysis*” OR “Fire fighting*”) AND ((“Human error*” OR “Mechanical failure*” OR “Violent reaction*” OR “Natural disaster*” OR “Vandalism*” OR “Attack*” OR “Erosion*” OR “Malpractice*” OR “Major accident*” OR “Chemical accident*” OR “Fire*” OR “Explosion*” OR “Leakage*” OR “Toxic release*” OR “Asphyxia*” OR “Domino effect*” OR “Traffic accident*” OR “Maritime accident*” OR “Industrial accident*” OR “Pandemic*” OR “Public health emergency*” OR “Construction accident*” OR “Nuclear accident*” OR “Theft*” OR “Medical accident*” OR “Financial fraud*” OR “Financial crisis*” OR “Cyber attack*” OR “Occupational accident*”) OR (“Pollution*” OR “Climate change*” OR “Ecological damage*” OR “Environmental damage*” OR “Radiation*” OR “Greenhouse effect*” OR “Extreme weather*” OR “Loss of life*” OR ”Quality of life*” OR ”Casualties*” OR ”Fatalities*” OR ”Injuries*” OR ”Moral*” OR ”Public health*” OR ”Physical health*”

Accident	Human error	OR ”Occupational health*” OR ”Mental health*” OR ”Psychological health*” OR“Property loss*” OR “Cost*” OR “Productivity loss*” OR “Economic burden*” OR “Financial liability*” OR “Bankruptcy*” OR “Equipment damage*” OR “Equity*” OR “Welfare*” OR “Cohesion*” OR “Ethics*” OR “Sustainability*” OR “Politics*” OR “Criminal*” OR “Justice*” OR “Reputation*” OR “Trust*” OR “Poverty*”)))
	Mechanical failure	
	Violent reaction	
	Natural disaster	
	Vandalism	
	Attack	
	Erosion	
	Malpractice	
	Major accident	
	Chemical accident	
	Fire	
	Explosion	
	Leakage	
	Toxic release	
	Asphyxia	
	Domino effect	
	Traffic accident	
	Maritime accident	
	Industrial accident	
	Pandemic	
	Public health emergency	
	Construction accident	
	Nuclear accident	
	Theft	
	Medical accident	
	Financial fraud	
	Financial crisis	
	Cyber attack	
	Occupational accident	
Environmental impacts	Pollution	
	Climate change	
	Ecological damage	
	Environmental damage	

	Radiation	
	Greenhouse effect	
	Extreme weather	
Human life	Loss of life	
	Quality of life	
	Casualties	
	Fatalities	
	Injuries	
	Moral	
Health	Public health	
	Physical health	
	Occupational health	
	Mental health	
	Psychological health	
Economic loss	Property loss	
	Cost	
	Productivity loss	
	Economic burden	
	Financial liability	
	Bankruptcy	
	Equipment damage	
Social influence	Equity	
	Welfare	
	Cohesion	
	Ethics	
	Sustainability	
	Politics	
	Criminal	
	Justice	
	Reputation	
	Trust	
	Poverty	

9. Appendix B - Pre-set keywords and search statement

This search statement was used for generating bibliometric data on 20 May 2021 from the Web of Science (WoS) Core Collection. The timespan was set from 1900-2021. This search resulted in 7232 bibliographic papers from 3617 journals.

10. Appendix C - Method analysis

(1) QRA (quantitative risk assessment)

Quantitative risk assessment (QRA) is an advanced systematic risk analysis approach to quantifying the risks associated with the operation of an engineering process, addressing the risk to people, the environment, and properties, etc. It is always used to determine the risk of the use, handling, transport, and storage of dangerous substances (Uijt de Haag and Ale, 1999). Cozzani et al. (2005) developed a quantitative risk assessment method for domino effects in the process industry, considering health-related values (individual risk and societal risk). Crippa et al. (2009) quantified the individual and societal risks related to the release of liquid chlorine. Li et al. (2016b) conducted a quantitative risk assessment of leakage failure of submarine oil and gas pipelines, considering the damage of properties. Most of these studies focused on quantifying the risk related to health value and economic value.

(2) Bayesian network

BNs are directed acyclic graphs for reasoning under uncertainty in which random variables and their dependencies are represented using nodes and directed arcs (Khakzad et al., 2014). Tang et al. (2016) used a Bayesian network to analyse the risk of emergent water pollution accidents. Jia and Lu (2013) developed a mission-oriented risk assessment methodology for naval vessel fire caused by non-contact explosions using a Bayesian network. Jiang et al. (2020) analyse the likelihood of maritime accidents along the main route of the Maritime Silk Road using a Bayesian network approach.

(3) GIS (Geographic Information System)

A Geographic Information System (GIS) is a tool with the ability to capture and analyse spatial and geographic data, mapping risks. Saidi et al. (2021) developed a GIS-remote sensing approach for forest fire risk assessment in Bizerte region, Tunisia. Neshat and Pradhan (2015) conducted a risk assessment of groundwater pollution combining Dempster–Shafer theory and GIS. Arrighi et al. (2018) used GIS for estimating flood risk caused by environmental hotspots, considering the flood hazard, hotspots exposure, and the expected severity of the environmental impacts.

(4) Fuzzy theory

Fuzzy theory has been widely used to take into account vague or ambiguous information, a notorious cause of inherent inconsistency in risk analysis (Giardina et al., 2014). Ilbahar et al. (2018) developed a fuzzy theory-based approach for risk assessment of occupational health and safety, providing reliable and consistent outcomes with more information on the uncertainty of decision-makers. Besides, Kaya and Kahraman (2008) used this method to evaluate air pollution levels. Shahriar et al. (2012) built a sustainability assessment approach using fuzzy-based bow-tie analysis for oil & gas pipelines.

(5) Cost-benefit analysis

Cost-benefit analysis (CBA) is an economic tool for comparing the benefits and costs of a given project or activity, supporting decision-making on the project or activity (Shreve and Kelman, 2014). CBA consists of four primary stages: (i) project definition, in which the reallocation of resources being proposed are identified (ii) identification of project impacts, including assessment of additionality (net project benefits) and displacement (crowding-out), (iii) evaluating which impacts are economically relevant, that is, quantifying the physical impacts of the project and (iv) calculating a monetary valuation, discounting, weighting and sensitivity analysis (Hanley and Spash, 1996). In the safety domain, it is always used for decision-making on safety investments and safety resource allocation. Oxenburgh and Marlow (2005) developed a cost-benefit analysis model for the economic assessment of occupational health and safety interventions in the workplace. Kull et al. (2013) developed a quantitative and stochastic CBA framework for flood and drought risk reduction in India and Pakistan, incorporating projected climate change impacts. Chen et al. (2020a) established a cost-benefit analysis method for domino effect management, considering safety values related to property losses, human losses, reputation, environmental damage, etc. Roque and Cardoso (2015) developed a computer-aided procedure for cost-benefit analysis in roadside safety intervention decision making, considering medical costs; loss of production; costs of property damage; administrative costs; and economic valuation of lost quality of life. Onuma and Tsuge (2018) established a cost-benefit management approach for decision-making on ecosystem-based disaster risk reduction with grey infrastructure.

(6) AHP (Analytic Hierarchy Process)

AHP is a structured technique for organizing and analysing complex decisions with multiple criteria (Khan et al., 2021). This approach requires establishing a hierarchy of decision elements (criteria) and then making comparisons between possible pairs in a matrix to give a weight for each element, and a consistency ratio (BalaSundareshwaran et al., 2019). Hou et al. (2014) establishing a real-time, dynamic early-warning model for dealing with sudden water pollution accidents in which AHP is used to estimate the impacts of pollution. Nuthammachot and Stratoulias (2021) developed a multi-criteria decision analysis based on AHP and GIS for forest fire risk assessment. (Abdul Wahab et al., 2014) used AHP to evaluate inherent safety strategies for Reducing Human Errors.

(7) Probabilistic risk assessment

Probabilistic risk assessment (PRA) is a comprehensive, structured, and logical analysis method aimed at identifying and assessing risks in complex technological systems for improving safety and performance (Stamatelatos et al., 2011). Van Coile et al. (2018) demonstrated that probabilistic risk assessment is commonly accepted as one tool for performance-based design in fire safety engineering. Worrell and Rochon (2015) developed a probabilistic risk assessment tool for fire risk assessment in the Nuclear Power Industry. Sakurahara et al. (2018) established an integrated methodology for fire probabilistic risk assessment of nuclear power plants considering failure mechanisms using a CFD (Computational Fluid Dynamics) code and using a Monte Carlo simulation.

(8) Cost-effectiveness analysis

Cost-effectiveness analysis (CEA) is an economic evaluation tool focusing on the relative costs and effects of a new intervention compared to the existing practice, which is dominated by concerns about small changes at the margin (Evans, 2008). It is always used in healthcare combining with quality-adjusted life-years (QALYs) in which the incremental cost-effectiveness ratios (ICERs) are represented by ratios between the cost of interventions and QALYs (Salkeld et al., 1997). Kunigkeit et al. (2018) conducted a cost-effectiveness analysis for home safety interventions to prevent falls in impaired elderly people living in the community. Besides healthcare, Cost-effectiveness analysis is also applied to decision-making on safety measures (Tint et al., 2010; Peltola et al., 2012)

(9) CFD (Computational Fluid Dynamics)

Computational fluid dynamics (CFD) is widely used in the safety domain supporting consequence analysis involving hazardous materials (Abuswer et al., 2013). Fire Dynamic Simulator (FDS) is a widely used CFD code for fire simulation considering fire-induced smoke (Abuswer et al., 2013). FLACS developed by GexCon is used to simulate toxic release and gas explosions in offshore oil and gas platforms and other process plants (Jallais et al., 2018). Besides, FLUENT software based on CFD is also widely used for consequence analysis (Liu et al., 2020).

(10) Monte Carlo method

Monte Carlo simulation is always used for modeling uncertainties that cannot be easily accounted for by analytical methods due to the intervention of random variables, avoiding complex mathematical calculations (Chen et al., 2021a). Au et al. (2007) adopted Monte Carlo method for compartment fire risk analysis, incorporating the uncertainties in the functionality of active fire measures. Bai (2014) used a Monte Carlo simulation for a risk assessment of CO_2 release along with abandoned wells in a CO2 sequestration site. Ramírez-Marengo et al. (2015) estimated the likelihood of vapor cloud explosion caused by process equipment failures using Monte Carlo simulation.

(11) Event tree

Event tree is a forward, top-down, logical modelling technique for exploring event evolution through a single initiating event and lays a path for assessing probabilities of the outcomes and overall system analysis (Khan et al., 2015; Chen et al., 2020b). Chu et al. (2007) established a time-dependent event tree approach for evacuees in building fires, estimating the expected number of deaths. Cheliyan and Bhattacharyya (2018) developed a fuzzy event tree analysis for quantified risk assessment of oil and gas leakage in offshore facilities. Kong et al. (2011) established a life safety risk assessment method based on event trees for building fires.

(12) Artificial neural network

Artificial neural network (ANN) may be defined as an information processing system similar to neural networks of the human brain, for tackling large-scale complex problems such as pattern recognition, non-linear modeling, and classification (Carafa et al., 2011). Jafari Goldarag et al. (2016) assessed fire risk using ANN model forest fire risk, recognizing high potential areas for fire occurrence. Naderpour et al. (2021) established a forest fire risk prediction method based on a spatial deep neural network.

(13) Questionnaire

A questionnaire is a research instrument consisting of a series of questions for gathering information from respondents (Fabiano et al., 2008). Fabiano et al. (2008) designed a questionnaire to identify technical, organisational, and individual factors of suffered injuries and find out how firms try to reduce the occupational risk to which temporary employees may be exposed. Denning et al. (2020) used a safety attitudes questionnaire (SAQ) to investigate safety culture at a large UK healthcare trust during Covid-19. Du et al. (2017) developed a questionnaire to evaluate the level of public acceptance of abrupt environmental pollution risks, analyse demographic differences in public attitudes toward abrupt environmental pollution risks, and explore the factors that influence the acceptable risk level tolerated by the public.

(14) FDS (Fire Dynamics Simulator)

FDS is a CFD (Computational Fluid Dynamics) code developed by NIST for simulating the fire-induced flow fields in a compartment, solving the transient governing equations for a low-Mach number turbulent flow (Sakurahara et al., 2018). Xu et al. (2017) used FDS to study fire smoke spreading and control in emergency rescue stations of extra-long railway tunnels. Sun and Turkan (2020) studied critical factors affecting human evacuation performance based on FDS.

(15) Index method

The index method is a simple and clear approach that is always used in the safety domain to measure some indicators or factors. Khan and Amyotte (2005) developed an integrated inherent safety index to quantify inherent safety and evaluate safety cost. Wu and Liu (2011) constructed an index system based on the factors impacting coal fire development for risk assessment of underground coal fire development at a regional scale. Saedpanah and Amanollahi (2019) established indexes for environmental pollution and geo-ecological risk assessment of the Qhorveh mining area in western Iran.

(16) Machine learning method

Machine learning is one of the big data analysis techniques which analyses data based on a given algorithm, learns the data through the analysis, and makes judgments or predictions based on the learning model (Phark et al., 2018). Dang et al. (2019) predicted fire risk in the Humberside area by using a machine learning method based on multi-source data. Phark et al. (2018) used a machine-learning algorithm to predict emergency evacuation orders.

(17) Economic analysis

Economic analysis in the safety domain is used to analyse economic issues related to safety including safety costs and safety benefits. Noh and Chang (2019) conducted an exergy-based economic analysis incorporating safety investment cost for comparative evaluation in process plant design. Daniels et al. (2019) analysed the economic costs of 29 road safety measures to make safety management more cost-effective.

(18) Game theory

Game theory which originated in economic sciences is a good tool to deal with problems with two or more players (Reniers and Pavlova, 2013). Zhao et al. (2020) built a finite-horizon semi-Markov general-sum game between plant operators and attackers to obtain the time-sensitive attack response strategy and the real-time risk assessment in nuclear power plants. Moradi et al. (2019) developed a cooperative game theory method for sustainability risk management in a cooperative environment under uncertainty.

(19) Analytical method

Analytic methods refer to the methods using exact theorems to present formulas without graphic presentation and numerical calculation. He et al. (2015) conducted a comprehensive risk assessment method considering natural disasters for power systems using an analytical method. Zhao et al. (2020) developed an analytical model for time-sensitive attack response and probabilistic risk assessment in nuclear power plants.

(20) Willingness to pay

Willingness to pay (WTP) represents the maximum money an individual is willing to pay for a risk reduction (Reniers and Van Erp, 2016). Vassanadumrongdee et al. (2005) measured individuals' willingness to pay (WTP) to reduce mortality risk arising from air pollution and traffic accidents in Bangkok, Thailand. Lai et al. (2018) investigated the impacts of Chinese consumers' risk perceptions on their willingness to pay for pork safety, environmental stewardship, and animal welfare. Mon et al. (2018) conducted a study to determine the costs related to fatality risk reductions using a willingness to pay (WTP) approach for motorcyclists, car drivers, and bus passengers in Myanmar. Akter (2020) studied the willingness to pay for cyclone risk reduction for the coastal embankment improvement project in Bangladesh. Sereenonchai et al. (2020)

investigated the risk perception on haze pollution and WTP for self-protection and haze management in Chiang Mai Province, Northern Thailand.

(21) Multi-criteria decision-making methods

Multi-criteria decision-making (MCDM) is an advanced field of operations research (OR), explicitly considering multiple criteria in decision-making. Mohandes and Zhang (2021) developed a holistic occupational health and safety risk assessment model based on a MCDM method for sustainable construction projects. Chen et al. (2020c) built a hybrid approach integrating MCDM and clustering for evaluating and comparing the regional risk to natural disasters in China. Gul (2020) constructed a MCDM approach for occupational health and safety risk assessment in the international port authority.

(22) Value of statistical life

The monetary value for preventing one statistical death is usually defined as the value of a statistical life (VSL), which may be considered as a special type of WTP (Chen et al., 2021b). It is always used in cost-benefit analysis to monetise the consequences of human loss in accidents (Robinson and Hammitt, 2015; Robinson et al., 2019). As a result, measuring the VSL is the key step to use safety economics in the decision-making on safety investment (Reniers and Van Erp, 2016; Mon et al., 2018)

(23) Genetic algorithm

Genetic algorithm (GA) is an evolutionary algorithm (EA) used for generating high-quality solutions to optimisation and search problems by relying on biologically inspired operators such as mutation, crossover, and selection (Whitley, 1994). Aihong and Lizhe (2012) developed a city fire risk assessment approach based on the adaptive genetic algorithm and BP network. Estepa et al. (2019) used a genetic algorithm to identify the cost-effective reliable networks from a risk analysis perspective.

(24) Petri-net

Petri-nets can be regarded as a graphical approach consisting of two sets of nodes (the set of places representing system objects and the set of events or transitions determining the dynamics of the system), which are always used to analyse and simulate concurrent systems (Chen et al., 2020b). Zhou and Reniers (2018) established a Petri-net-based evaluation of emergency response actions for preventing domino effects triggered by fire. Li et al. (2016a) modelled subway fire emergency response using a Petri-net. Kamil et al. (2019) developed a dynamic domino effect risk assessment using Petri-nets.

(25) Hazop

Hu et al. (2018) established a structured hazard identification method based on Hazop for human error for shale gas fracturing operations. Mohammadfam and Zarei (2015) developed a safety risk model for major accidents of hydrogen and natural gas releases based on Hazop.

(26) Risk matrix

A risk matrix is a matrix used for risk assessment by defining the level of risk by considering the likelihood against the consequence severity. Shariff and Zaini (2013) developed a risk matrix for inherent risk assessment in the preliminary design stage. Gul and Ak (2018) established a comparative outline for quantifying risk ratings in occupational health and safety by a risk matrix. Pang et al. (2021) established a risk matrix for the risk assessment of polyethylene dust explosion based on explosion parameters.

(27) Big data

Big data usually includes data sets with sizes beyond the ability of commonly used software tools to capture, curate, manage, and process data within a tolerable elapsed time. Phark et al. (2018) used big data and machine learning to predict the issuance of emergency evacuation orders for chemical accidents.

(28) Bow-tie model

The Bowtie method is a risk evaluation method that can be used to analyse and demonstrate causal relationships in high-risk scenarios (Khakzad et al., 2012). Zhang et al. (2020) conducted a risk analysis of high-pressure gas pipeline leakage based on the bow-tie model.

(29) FEM (Finite element analysis)

Finite element analysis (FEA) is a numerical computation method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects (Szabó and Babuška, 1991). In the safety domain, it is always used for consequence analysis. Farrahi et al. (2018) conducted a failure analysis of bolt connections in the fired heater of a petrochemical unit. Yong and Guo-qiang (2013) established a loading-bearing capacity method based on FEA for structural fire safety design.

(30) G1 method

G1 is an order-relation analysis method that can be used to obtain the weights of each index (Gong et al., 2021). Gong et al. (2021) classified emergency responses to fatal traffic accidents in Chinese urban areas using the G1 method. Liya and Weike (2009) studied the emergency response ability evaluation of gas pipelines.

(31) Graph theory

Graph theory is always used for modeling complex systems with multiple agents (Chen et al., 2020b). Anand et al. (2016) used graph theory to model a mechanical system for risk assessment of the system. Dai et al. (2015) developed a risk flow attack graph-based approach for risk assessment. Chen et al. (2020a) established a cost-benefit analysis for domino effect management based on dynamic graphs.

(32) Human capital method

Human capital approach is a method to estimate the indirect cost due to productivity loss by calculating the present value of the income stream foregone due to premature death (Reniers and Van Erp, 2016). Nuñez and Prieto (2018) analysed the impacts of firms' human capital on their investments in occupational health and safety. Steel et al. (2018) performed a systematic search of economic evaluations of OHS programs published between 2007 and 2017 and found that the human capital approach is the most frequent method. Nuñez and Prieto (2018) conducted an empirical analysis of the effect of human capital on occupational health and safety investment in Spanish firms.

(33) Information diffusion model

The information diffusion model is a fuzzy mathematic set-value method for samples, considering optimizing the use of fuzzy information of samples to offset the information deficiency (Chu et al., 2014). Chu et al. (2014) studied LNG terminal station fire risk using the information diffusion model. Zhong et al. (2010) used an information diffusion model for natural disaster risk assessment of grain production in Dongting lake area, China.

(34) Interview

An interview is a research method for eliciting detailed information from interview participants who are asked a series of questions by interviewers (Irwin and Poots, 2015). Ball et al. (2013) used a semi-structured interview to find out possible models for flood insurance that would be satisfactory to the industry, consumers, and other stakeholders. Cvetković et al. (2021) investigated nuclear power risk perception in Serbia (fear of exposure to radiation vs. social benefits) by using a face-to-face interview. Maslen (2019) studied how organisations cultivate values, and whether the promotion of safety as a value is a robust approach to major accident risk management using semi-structured interviews.

(35) Prospect theory

Prospect theory deems that individuals' preferences and behaviours under risk and uncertainty tend to follow the evaluation of an individual's potential possible gains and losses (Kahneman and Tversky, 2013). Leung and Cai (2021) developed and tested an integrated model of perceived risk with a moderating role in pandemic severity based on prospect theory. Chen et al. (2019) extended HFACS based risk analysis approach for human error accidents using prospect theory. Kazancoglu et al. (2020) conducted a risk assessment for sustainability in e-waste recycling in a circular economy.

(36) QALYs (Quality-adjusted life-years)

QALYs provide a very intuitive method combining two main components of health (i.e., life duration and quality of life) into a single index which is widely used in health care policymaking (Garcia-Hernandez, 2014). Robinson and Hammitt (2015) valued health risk reductions in benefit-cost analysis using QALYs. Garcia-Hernandez (2014) developed a formulation of the QALYs model used in benefit-risk assessment.

(37) Risk index

Risk indexes are a special type of index used for risk assessment. (Choi and Jun, 2020) developed fire risk assessment models using statistical machine learning and risk indexes. Li et al. (2020) developed a risk assessment method and a forewarning model for groundwater pollution by using a risk index method. Zhou et al. (2019) used the potential ecological risk index for a risk assessment of potentially toxic elements pollution from mineral processing steps at Xikuangshan Antimony Plant, Hunan, and China. Song et al. (2021) established a quantitative risk assessment of gas leakage and explosion accident consequences inside residential buildings using explosion indexes.

11. Appendix D - Value of Safety Survey Questions

Definition of safety

1. From your personal perspective, how do you define safety? (Please select one option only)

£ A psychological state without fear of negative consequences.

£ A physical state with relative freedom from hazards, injuries, or loss of personnel and property.

£ A condition or judgment of acceptable control over negative consequences caused either deliberately or by accident.

£ Others, please specify____________

2. From your organisation's perspective, how do you define safety? (Please select one option only)

£ A psychological state without fear of negative consequences

£ A physical state with relative freedom from hazards, injuries, or loss of personnel and property

£ A condition or judgment of acceptable control over negative consequences caused either deliberately or by accident.

£ Others, please specify____________

Categories of the Value of safety

1. What general values/terms do you think are associated with safety? （Please feel free to select more than one option）

£ Environmental

£ Economic

£ Ethics

£ Health and life

£ Justice

£ Resilience

£ Reputation

£ Scientific

£ Sustainability

£ Others, please specify____________

______________________________ __________________________
______________________________ __________________________
______________________________ __________________________
______________________________ __________________________

2. Your organisation may implement safety interventions to prevent negative consequences with respect to the following aspects. Please rank their importance with a figure of 1 to 5 (5 means the most preferable/important one).

Health and life____

Environment___

Economic___

Ethics___

Reputation___

Other, please specify and rank ___

MEASURING the VALUE OF SAFETY

1. What approaches are used by your organisation to measure the value of safety? （Please select one option only）

£ Qualitative approaches

£ Quantitative approaches

£ Combination of the above approaches

£ Others, please specify____________

2. What approaches are commonly used by organisations in your sector to measure the value of safety? (Please select one option only)

£ Qualitative approaches

£ Quantitative approaches

£ Combination of the above approaches

£ Others, please specify___________

3. Which ones of the following types of approaches is used by your organisation to measure the value of safety and what types of value (health and life, environment, economic, ethics, reputation, et al.) is measured by the approach? （Please feel free to select more than one option）

£ Survey/questionnaire is used to measure____________________value(s)

£ Index-based approach is used to measure____________________value(s)

£ Capital approach is used to measure____________________value(s)

£ Risk assessment is used to measure____________________value(s)

£ Resilience assessment is used to measure____________________value(s)

£ Cost-Benefit analysis is used to measure____________________value(s)

£ Computer simulation is used to measure____________________value(s)

£ AI and data-driven approaches is used to measure____________________value(s)

£ Others___________

4. Which ones of the following types of value of safety are not sufficiently analysed and properly measured by your organisation? （Please feel free to select more than one option）

£ Environmental value

£ Economic value

£ Ethics value

£ Health and life value

£ Justice value

£ Resilience value

£ Reputation value

£ Scientific value

£ Sustainability value

£ Others, please specify____________

5. In your opinion, what approach(es) should be further developed to support consideration and measurement of the values (selected in Q4) that aren't sufficiently analysed by your organisation?

______________________________ ___________________________

______________________________ ___________________________

______________________________ ___________________________

______________________________ ___________________________