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Assessing the Risk of Hazards with Multidimensional Consequences for Industrial Processes

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Abstract: Risk assessment plays an important role in process safety. The result of the assessment is used to determine risk priorities and then develop preventions to reduce risks. A hazard may have multidimensional consequences, including loss of health and safety, asset loss, and environmental damage. Traditionally, these multidimensional consequences are often measured disjointedly. A comprehensive risk assessment would be conducted by many professionals from multiple areas. Each of these professionals uses different indicators to evaluate risks. The poor integration among risk indicators further confuses managers in the risk resilience and prevention development. In addition, this lacks a solid method for assessing the risk of hazards that with multidimensional consequences. The aim of the work is to develop a risk-measuring instrument using a newly proposed approach, the Risk Assessment for Hazards with Multidimensional Consequences (RAMC), which is developed based on the theory of quality of life (QOL), a theory from health management. RAMC uses the 'diminished quality of life in organization safety' (DQLOS) as a risk indicator to represent the level of risk exposure. The main results of the work show that the method of RAMC and the indicator 'DQLOS' are able to support practitioners to assess the risk of a hazard with multidimensional consequences and could be used to deliver reasonable risk control priorities. A case study associated with the coal-to-methanol gasification process is discussed for RAMC's application and validation. The case study result also indicates that the DQLOS has the potential to assist the industry to design safe process systems and develop ongoing improvements in safety.

Keywords: risk assessment; hazards with multidimensional consequences; risk measuring instrument; process safety

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1. Introduction

Risk assessment (RA) plays an important role in safety [1,2], and it has rich applications in the chemical industry. Existing risk assessment methods are, e.g., Hazard and Operability Study (HAZOP) [3], Fault Tree Analysis (FTA) [4,5], Failure Modes and Effects Analysis (FMEA) [6,7], and Bowtie [8]. Risk is the product of consequence and likelihood [9]. A hazard is any chemical, physical or biological source that can cause negative outcomes to people's health, environment, and assets [10]. The analyzers use the above tools to examine potential hazards and determine risks by evaluating the likelihood of an unwanted event arising and the corresponding severity of the consequence. The analyzers examine the likelihood and consequence either based on the historical incident records or their subjective evaluation based on their professional knowledge and experience [11]. Some recent works are associated with the development of Human Reliability Analysis (HRA) for evaluating human error probability (HEP) [12,13].

A comprehensive safety assessment requires us to consider multiple aspects of consequences of risks. Figure 1 illustrates the multidimensional consequences associated with the process industry, including individual injures, asset loss, environmental damage, etc. [14,15]. Managing risk is like solving puzzles, the analyzers are expected to put all puzzles together—comprehensively consider the risk—and arrive at the correct solution for risk minimization. A comprehensive risk assessment should be obtained by many professionals, such as fire chiefs, industrial hygienists, project managers, structural engineers, etc. This is for the breadth of the assessment and is proposed by ISO31000 in 2018 [16].

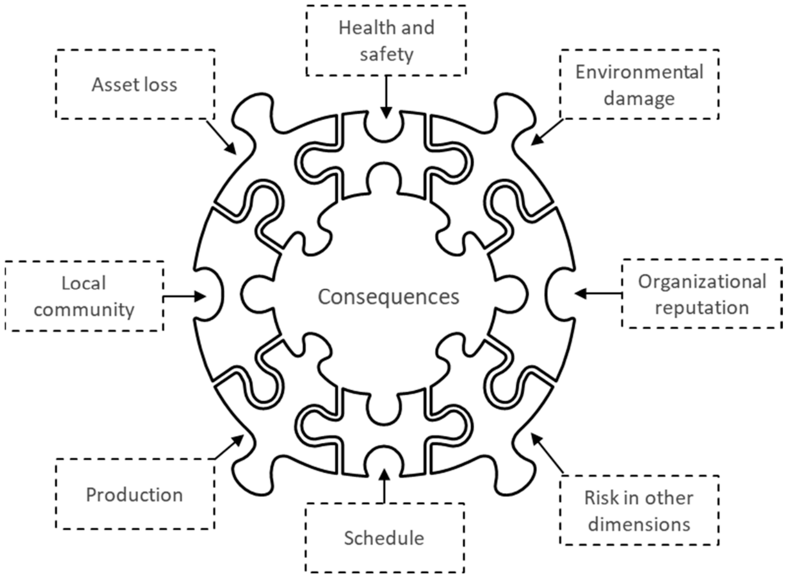

Figure 1. Multidimensional consequences.

Successful implementation of safety management requires an effective mechanism to assess risks. Many consequences are often overlapping with each other and may originally come from the same hazard [17]; for example, an explosion would cause asset loss, injuries, environmental pollution, and organizational reputation damage. The existing methods do consider consequences with multidimensions, but they usually judge the corresponding risks disjointedly and weigh them subjectively [18]. Lacking such a systematic method in assessing the risk of hazards with multidimensional consequences would result in poor consistency between experts. This may further cause inefficient risk responses. This is deeply problematic because recent policies on safety have made it necessary for organizations to consider other impacts simultaneously, e.g., health and safety, and environmental damage. However, there is no coherent method for assessing the risk of hazards with multidimensional consequences. Consequently, the primary aim of the current work is to develop such a solid and coherent method for examining the risk for the hazards with multidimensional consequences. To achieve this goal, the paper explores a new risk assessment method, namely Risk Assessment for Hazards with Multidimensional Consequences (RAMC), which uses the theory from health management—"quality of life"—to solve the problem and proposes a novel concept, namely "diminished quality of life in organization safety" (DQLOS), as a measurement for the risk examination. RAMC register is also developed for industrial application. The findings of the work would further be used in risk minimization, risk exposure monitoring, and safety system design.

The rest of the paper is organized as follows. Section 2 illustrates the gaps of the existing safety assessment methods. Section 3 indicates the overall development of RAMC. Section 4 presents a case study of the RAMC to evaluate the risk of a gasification process in a coal-to-methanol plant. Section 5 discussed the novel contributions of RAMC and the comparison with conventional risk assessment methods. Section 6 concludes the overall work.

2. Related Work

2.1. Gaps of the Conventional Safety Assessment Methods

Professionals with different backgrounds evaluate the risk using their measuring indicators. There are multiple measuring indicators that exist in different areas, and there are even multiple indicators in one same area, see Table 1. Professionals would determine control priorities based on the risk outcomes and develop response strategies. However, using multiple indicators in one risk assessment would create a series of problems: (a) how do you conclude the final risk outcomes? (b) which hazard is the most dangerous/risky? and (c) should we weigh the risk of multidimensional consequences equally or differently? Existing methods have trouble solving those questions. Previous studies also gave relatively less consideration to the weight between different risk dimensions. Some traditional methods use the cost in economics as an indicator of risk [19], but this is not efficient in some aspects, e.g., long-term health. Disjointed consideration of multidimensional consequences would result in unwise decisions. Some negative outcomes could be, for example, inefficient risk resilience, struggling with response priorities, and poor prevention development.

Table 1. Example of the Risk Measuring Instruments in Different Risk Dimensions.

Categories of Risk	Measuring Instrument
Loss in health and safety	• Long-term health: quality of life (QOL) [20,21], diminished quality of life (DQL) [22], quality-adjusted life year (QALY) and disability-adjusted life year (DALY) [23]; • Short term safety: Falling from height [24]; • ISO31000: Risk management [16];
Asset loss	• Value at risk (VaR) [25,26]; • ISO27001: Asset-based risk assessment [27];
Environment damage	• ISO14005: Environmental management systems [28]; • Lifecycle assessment, e.g., energy assessment and carbon emissions assessment [29].

To address the aforementioned issues, this paper explores a novel way in safety risk assessment, hence the integration of QOL. QOL is a theory to quantify individual health; it is defined by World Health Organization (WHO) as "an individual's perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns". There are similarities between individual health and the organization safety [30]. The risk of a hazard determines the potential loss in QOL, hence 'diminished quality of life' (DQL) [22]. In an individual perspective, the risk of a hazard is associated with DQL in individual health. In an organization perspective, we propose that the risk of a hazard is associated with the 'diminished quality of life in organization safety' (DQLOS). The definition of DQLOS is further given in Section 3.4.

2.2. Existing AHP Applications in Safety

The challenge of the work is to develop a standard risk indicator for multidimensional consequences. Here, Analytic Hierarchy Process (AHP) is used to develop such measurement. AHP is a structured tool using for group decision making in complex decisions [31]. AHP is a theory of measurement and a priority decision method for multiple attributes. It helps people to determine the most desired solutions based on the quantifying criteria values, through pairwise comparisons. The AHP has a special consideration for pairwise consistency, and it measures the dependence between each attribute in the relation hierarchy. Making choices based on AHP happens in four steps [31], as seen in Table 2. In this work, weights are used to represent the impacts of a consequence to organization safety. The greater the weight of a consequence, the higher the severity indicator is represented, and the more quality of life would diminish in organization safety.

Table 2. Four Steps of AHP Application.

Application Sequences		Task Description
Step 01:	Problem structure.	Define the problem and parameters. Structure the hierarchy.
Step 02:	Intensity evaluation.	Determine the importance between parameters. Obtain the pairwise matrix. Consistency judgement of the intensity.
Step 03	Weight computation.	Compute the weights of each parameter.
Step 04	Decision making based on prioritization.	Conduct comparisons based on the weights and making decisions.

Traditional risk assessments are usually subjective, so they may lack consistency in judgement. Recent studies have shown that subjective assessments often disagree with their counterparts [32]. The use of AHP in risk assessment development has a potential to solve this inconsistency. AHP has many applications in engineering, e.g., quality management [33], production management [34], and operational performance management [35]. In the field of safety assessment, there are many studies that use AHP to determine the severity of hazards [36,37]. Applications can be found in areas of musculoskeletal disorder [38], communication systems [39], fire control systems [40], and underground mining [41]. Some other safety works use AHP to compromise safety issues associated with budgeting [42] and transportation [43]. Fuzzy AHP (FAHP) has also been developed to assist the risk decision making with ambiguous data and imprecise knowledge [44–46]. Although AHP has rich literature in safety, the use of development in risk measurement is relatively rare.

3. The RAMC Method

3.1. Purpose of the Work

The primary aim of the work is to develop a quantitative method for industries to assess the risk of hazards with multidimensional consequences. Although the examination area is the process industry, the proposed RAMC is suitable for general application, and it can also be applied to other industries, e.g., manufacturing and construction.

3.2. Determine Level of Consequence

An unsafe event often contains multiple consequences, and they are with multiple dimensions. In the current work, three dimensions, including environmental damage, asset loss, and health and safety, are discussed and used to explain the concept of the consequence scaling. Other dimensions of consequences are also suitable for using the proposed method. To determine the level of consequence, the first step is to identify all potential hazards and their consequences. This happens via hazard examination. Then we use AHP to examine each weight of the consequences. Figure 2 illustrates an example of the AHP examination of hazards and multidimensional consequences. The combination of parameters represents the consequence outcomes of one unsafe event; e.g., E_1, E_2, A_1, H_1, and H_2 are the consequence outcomes of Event 01. The pairwise comparison is then applied between parameters using the matrices proposed by [31] for weight examination, as shown in Table 3.

After the pairwise comparison between parameters, the pairwise matrices A can be obtained, as shown in Equation (1).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

where a_{ij} expresses the pairwise intensity regarding a_i to a_j. Alternatively, $a_{ij} = \frac{1}{a_{ji}}$ and $a_{ii} = 1$ $(i, j = 1, 2, \ldots, n)$. n represents the number of parameters.

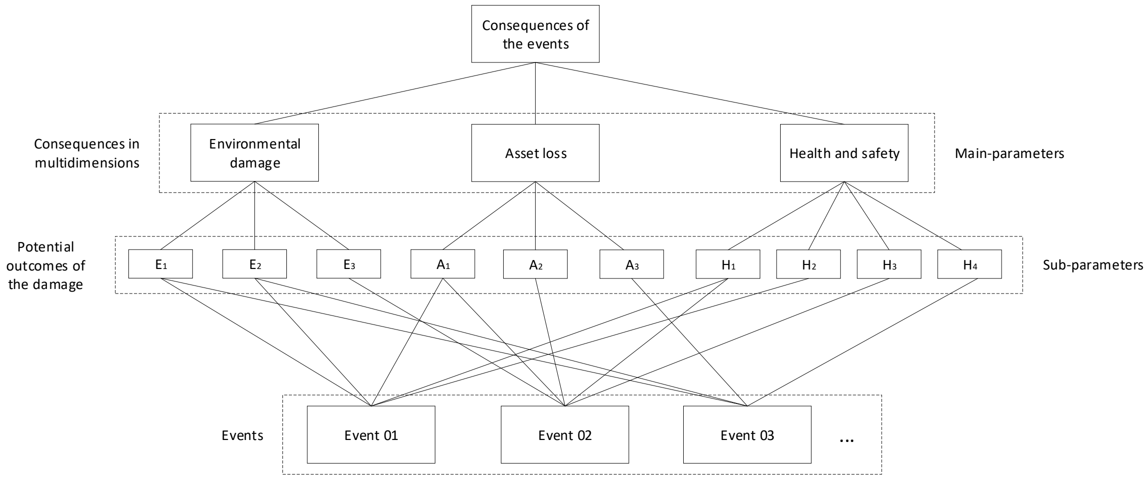

Figure 2. Example of AHP examination in consequences; E_n, A_n, H_n represents the potential outcomes of the damage in different dimensions.

Table 3. The Pairwise Comparison Scales.

Intensity of Importance (x)	Definition of the Importance
1	Equal importance between two parameters.
3	Moderate importance of one over another parameter.
5	Strong importance of one over another parameter.
7	Very strong importance of one over another parameter.
9	Extreme importance of one over another parameter.
2, 4, 6, 8	Intermediate values between two intensities of judgments.
Reciprocals (1/x)	Inverse comparison between two parameters.

The next step is to compute the consistency ratio (CR) of each pairwise matrix, see Equation (2). The concept of AHP theory and Equations (1)–(3) are developed by Saaty, see [31].

$$CR = \frac{CI}{RC} \tag{2}$$

RC is the random consistency index which can be determined in Table 4 [31]. Consistency index (CI) can be evaluated using Equation (3) [31].

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

where the λ_{max} is the maximum eigenvalue of the pairwise matrix. For a reliable comparison, the CR should be less than or equal to 10% [31].

Table 4. Random Consistency.

n	1	2	3	4	5	6	7	8	9	10
RC	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The intensity determines the weight between parameters, and the weight of a parameter can be computed using Equation (4). The severity of each consequence can be determined based on the weights. The use of weight to determine the loss in safety is further discussed in Section 3.4.

$$\text{Weight} = \frac{\text{Intensity value of the parameter}}{\text{Sum of the intensity value of the group}} \tag{4}$$

3.3. Determine Level of Likelihood and Frequency

Both the frequency of an event arising and the likelihood of a consequence arising can be examined based on historical data or subjective assessment. In the RAMC method, the frequency and likelihood in risk computation are both using probabilities. Hence, they are using the same measurement scale. The Words to Estimate Probability (WEP) for likelihood and frequency descriptions is applied here for the measurement development. WEP is developed by Sherman Kent [47] and uses quantitative words, e.g., likely, unlikely, and impossible, to describe the probability of an event arising. A probability scale is then developed to quantify the level of the likelihood/frequency for risk measurement. The proposed likelihood/frequency scale is shown in Table 5, modified from [22,32,48].

Table 5. Likelihood and Frequency Measuring Scale.

Likelihood Description	Frequency Description	Probability
Almost certain	At least once a year.	90%
Likely	Has occurred multiple times in your career.	70%
Possible	Might occur once in your career.	50%
Unlikely	Event does occur somewhere from time to time.	30%
Rare	Heard of something like this occurred.	7%
Almost incredible	Theoretically possible but never occurred.	1%

There are limitations in both historical-data-based and subjective-assessment-based likelihood and frequency examination. The WEP method is lacking data support, and it mainly relies on individual's knowledge and experience, so it may lack consistency and reliability. In contrast, the historical-data-based method is quantitative and is efficient to be used for assessing the frequency of safety incidents, e.g., fall from height, and the likelihood of consequence arising. Historical data are recorded by safety incident reporting systems such as Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR), which include the cause of the unsafe events, corresponding consequences, etc. These data are valuable for frequency, likelihood and severity estimation. In chemical process, there have also been many historical operational data recorded by operational systems, e.g., Distributed Control System (DCS). These data are useful for examining the occurrence of the unwanted event arising. However, the historical-data-based method may be inefficient to determine the likelihood and frequency of those incidents being "high consequence but low frequency" (HCLF), e.g., explosions. HCLF incidents are common in chemical industry. Alternatively, some other historical data associated with long-term health is weakly recorded in the industry, so it is seldom used for the likelihood and frequency estimation. Therefore, the historical data is not always efficient in likelihood and frequency determination. Consequently, there is a need to integrate the two methods as a solid one for likelihood and frequency estimation. A methodology for integrating WEP method and historical data method for likelihood and frequency estimation is proposed in the author's previous work [32].

3.4. Measuring Risk Using DQLOS

We now propose a new concept using QOL theory to measure the risk that integrates all of the above. The safety effects of an unsafe event can be measured by "diminished quality of life in organization safety"; thus, DQLOS, which refers to the multidimensional loss caused by the hazards which would affect the organization's safety. Adopting the concept in QOL causes a greater DQL and a greater loss in individual health. Thus, in an organization safety perspective, the greater the DQLOS, the greater the loss associated with organization safety. The measurement range of DQLOS is from 0 to 1. Zero refers to no effect on organization safety, and one represents catastrophe impact, for example, people's deaths. Equations (5) and (6) illustrates the computation of DQLOS.

$$\text{DQLOS} = \sum_{i}^{n} F_i L_i C_i \tag{5}$$

and

$$\sum_{i}^{n} C_i \leq 1 \tag{6}$$

where DQLOS represents the total risk of a hazard that would cause multiple consequences, F_i represents the frequency of the hazard arising, L_i represents the likelihood of i_{th} consequence arising, C_i represents the severity of i_{th} consequence. n represents the number of dimensions of the consequences.

A hazard may have different severity of consequences; for example, a hit could cause serious harm to people, such as bone injury, or it could also cause a minor harm, such as abrasion, and each of the consequences has a different likelihood of arising. With this in mind, the concepts of frequency and likelihood are proposed in DQLOS computation. Both frequency and likelihood used in the RAMC risk computation are associated with probabilities, but with different meanings in risk. The frequency is associated with hazard activation, and the likelihood is associated with the consequence arising. An application of RAMC is further given in Section 4.3. The development of the RAMC risk register is also for the DQLOS implementation in practice.

3.5. The Overall Workflow of RAMC Application

The overall methodology of the RAMC application is illustrated as shown in Figure 3. Hazards are firstly identified using traditional methods, e.g., HAZOP, FTA, and Bowtie, and we then analyze the consequence, frequency and likelihood. Route A is used for determining the severity of consequence, and Route B is used for determining the frequency of the hazard arising and the likelihood of the consequence arising. This is followed by DQLOS computation and risk determination.

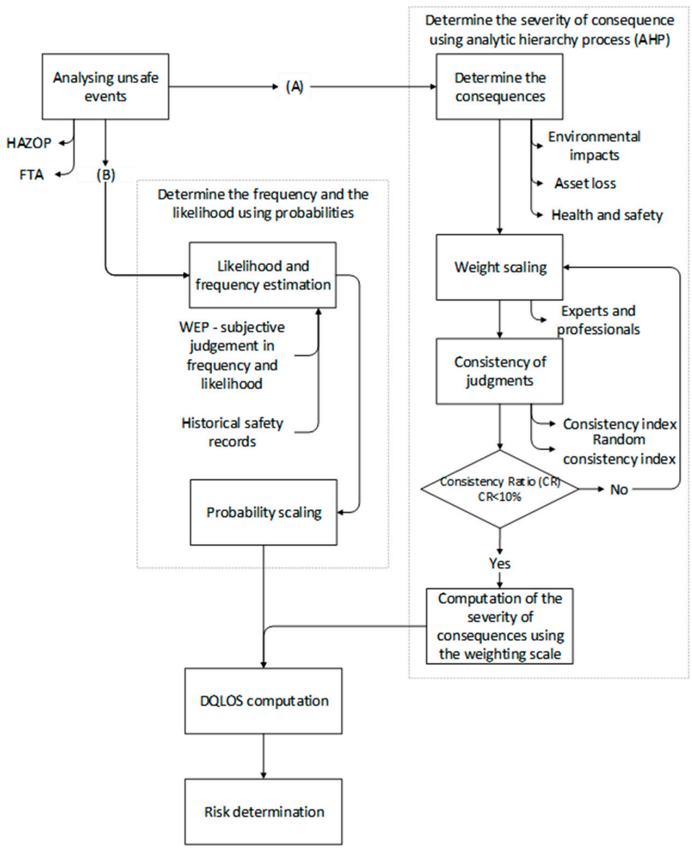

Figure 3. Workflow of the RAMC.

4. Application of RAMC

4.1. Hazards Assessment of Coal-to-Methanol Gasification Process

A coal to methanol gasification process is a process that uses coal slurry to produce syngas. The reactions are within a gasifier. The operational environment is shown in Figure 4. The risk assessment is obtained based on the simulation environment. This is a risk examination process before implementation in the real production.

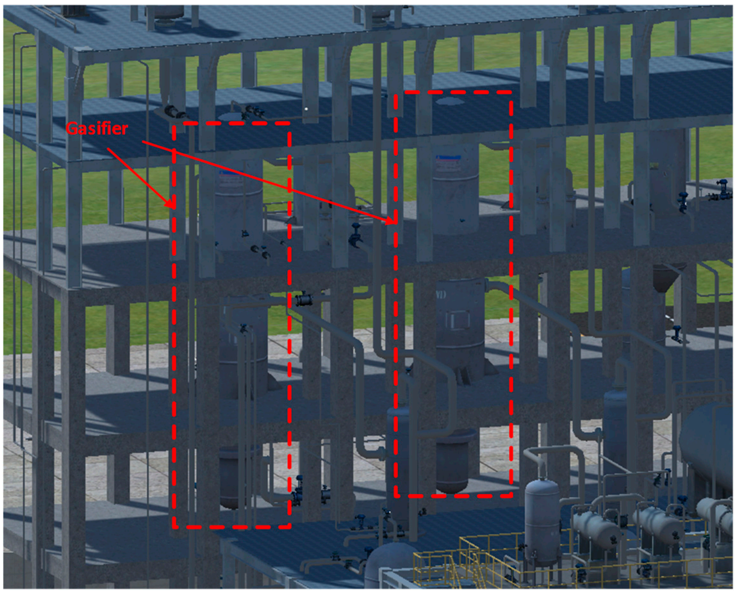

Figure 4. Gasifier of coal-to-methanol process in simulation.

A list of hazards is firstly aggregated from multiple sources including Health and Safety Executive (HSE), Occupational Safety and Health Administrations (OSHA), World health Organization (WHO), and existing studies [49,50]. The hazardous events of the gasification process are examined as shown in Table 6.

Table 6. Hazards Assessment for Coal-to-Methanol Gasification.

Hazardous Events	Description	Categories	Consequences
Explosion of gasifier	Explosion due to extreme pressure in the gasifier.	Health and Safety (H&S)	Worker injury or death
		Asset loss	Device damage due to the explosion
		Environmental damage	Air, water, and soil pollution due to the raw product release. The release of acid steam into the atmosphere would also affect flora and fauna.
Leakage of toxic gases	Toxic gas release throughout gasification.	H&S	Respiratory systems harm to workers and even death
		Environmental damage	The leakage may also result in air pollution and further have negative impacts on flora and fauna.
Fire disaster	Fire hazard due to release of gases during gasification.	H&S	Server occupational injuries caused by burn or events resuling in death
		Asset loss	Asset loss in devices, houseware, and building
		Environmental damage	Air and water pollution.
Burns and scorches	Caused by contact hot gasifier surfaces, hot water and leaking steam.	H&S	Skin burns.
Falls from height	Caused by slips, wet floor due to the bad weather, poor lighting environment.	H&S	Worker injuries including musculoskeletal damage, or even death

4.2. Severity of Consequences Examination

A consequence hierarchy was constructed with three main parameters including environmental damage, asset loss, health and safety. Each of the main parameters was further divided into sublevel parameters. Figure 5 is the AHP diagram representation of Table 6. The first pairwise comparison is between the three main parameters and then the sublevel parameters. λ_{max} and CR is computed for examining the consistency of weight scaling. There is a standard procedure to obtain the pairwise intensity data in the content of the theory of AHP [31]. In our case, we have three researchers performing as a safety investigation team to determine the intensity among different safety dimensions. While applying to industrial cases, such a safety investigation team would consist of several professionals from multiple backgrounds, for example H&S representative, fire engineer, and worker's team leader. Although the intensity estimation is subjective, it is further examined by the consistency ratio for its reliability. Pairwise matrices between parameters in the coal-to-methanol gasification process are illustrated in Table 7.

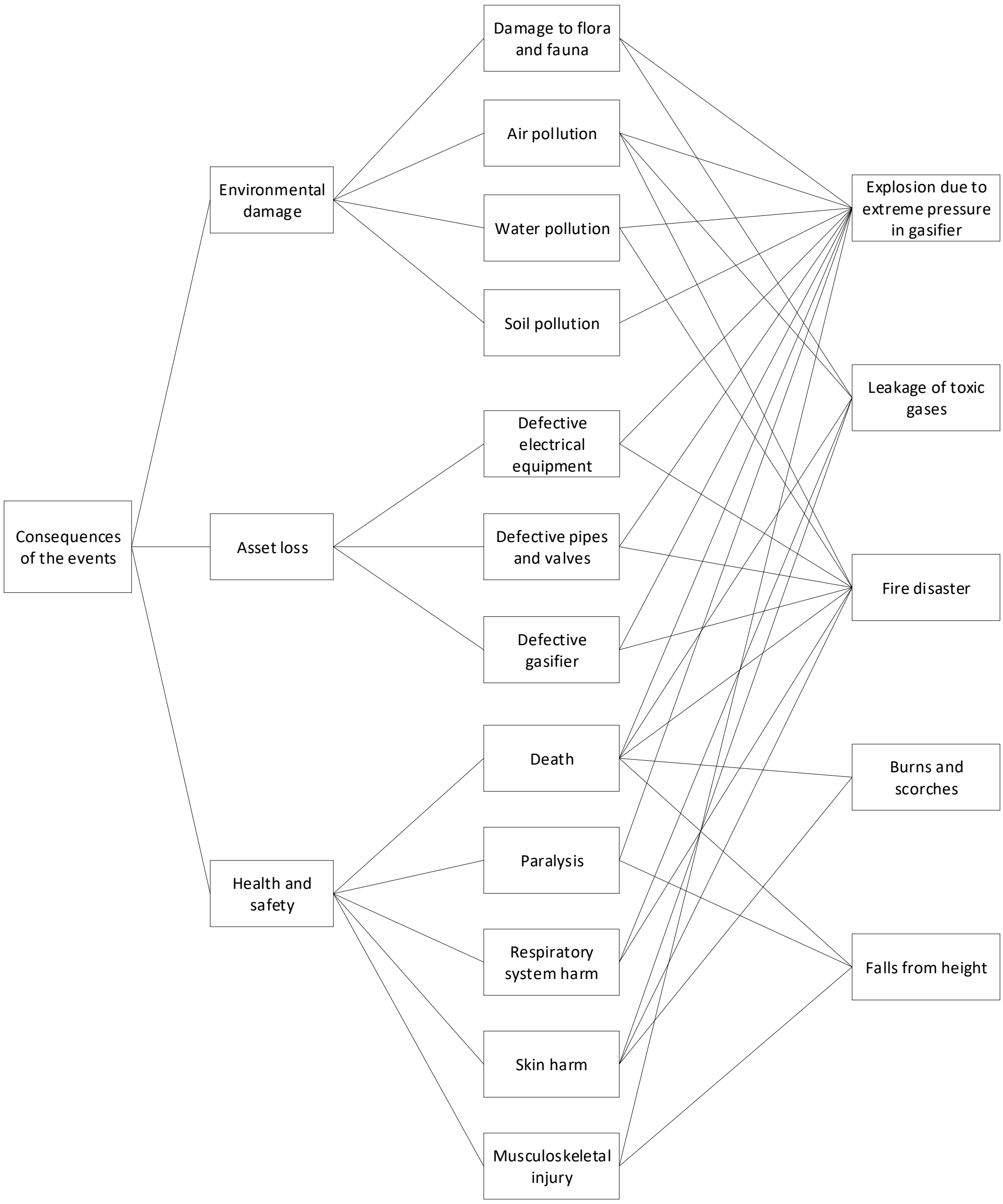

Figure 5. The hierarchy relations between safety events and consequences in different dimensions.

Table 7. Pairwise matrix between parameters.

Parameters / **Pairwise Matrix**

(**a**) Main-weight examination: Pairwise matrix of environmental damage, asset loss, and health and safety

	Environmental damage	Asset loss	Health and safety	Weighting
Environmental damage	1	1/2	1/3	0.16
Asset loss	2	1	1/2	0.30
Health and safety	3	2	1	0.54
λ max = 3.0092, CI = 0.0046 < 10 %				

(**b**) Subweight examination: Pairwise matrix of environmental damage

	Damage to flora and fauna	Air pollution	Water pollution	Soil pollution	Weighting
Damage to flora and fauna	1	1/5	1/3	1/2	0.09
Air pollution	5	1	2	2	0.45
Water pollution	3	1/2	1	1	0.24
Soil pollution	2	1/2	1	1	0.22
λ max = 4.0155, CI = 0.0052 < 10 %					

(**c**) Subweight examination: Pairwise matrix of asset loss

	Defective electrical equipment	Defective pipes and valves	Defective gasifier	Weighting
Defective electrical equipment	1	1/3	1/4	0.12
Defective pipes and valves	3	1	1/2	0.32
Defective gasifier	4	2	1	0.56
λ max = 3.0183, CI = 0.0158 < 10 %				

(**d**) Subweight examination: Pairwise matrix of health and safety

	Death	Paralysis	Respiratory system harm	Skin harm	Musculoskeletal injury	Weighting
Death	1	2	9	9	3	0.46
Paralysis	1/2	1	7	7	2	0.29
Respiratory system harm	1/9	1/7	1	1	1/3	0.05
Skin harm	1/9	1/7	1/3	1	1/3	0.05
Musculoskeletal injury	1/9	1/2	3	3	1	0.15
λ max = 5.0209, CI = 0.0047 < 10 %						

4.3. The Risk Examination

The risk examination can be seen in the spreadsheet, and the application to the gasification safety is shown in Figure 6. The risk register consists of seven columns. Column A is used for identifying hazards at work. Column B is a description of the hazardous event. Column C determines the frequency of that event arising. Column D is for determining the severity of consequence. The main weights in Column D are associated with the main parameters; in our case, they are associated with the three main parameters, hence the loss in H&S, assets, and environment. The subweights are related to the subparameters of the consequences, taking environment damage dimension as an example, the subparameters are, e.g., soil pollution and air pollution. The main weights and subweights are computed using the pairwise matrix shown in Table 7. Column E determines the likelihood of the consequence arising. In our case, the coal-to-methane gasification process is at the design status, so we are lacking such historical data to examine the likelihood of event arising. The likelihood of an event arising here is determined using the WEP method and evaluated by the domain expert team. This is a common subjective evaluation in general risk assessment, especially in the early design process. In industrial applications, there might be historical safety data existing for examining the frequency of unsafe events arising, and this can be used for likelihood estimation. Column F computes the sub-DQLOS, and Column G represents the final risk outcome based on DQLOS. The risk register is developed for multiple users who may become involved with the risk assessment. Potential users include engineering technologists and health and safety representatives. Risk priorities are determined based on DQLOS. Table 8 addresses the thresholds of DQLOS and also the corresponding responses.

Risk Register										
A	B	C	D					E	F	G
List of hazards	Event description	Frequence of the invident arising (F)	Severity of consquences determination					likelihood of the consequence arising (L)	Sub-DQLOS (F x L x C)	Level of risk (DQLOS)
			Cagetories of consequences	Main-weight (M)	Severity description	Sub-weight (S)	Level of consequence (C=M x S)			
Explosion of gasifier	Explosion due to extreme pressure in the gasifier.	7%	Health and Safety (H&S)	0.54	Death	0.46	0.248	70%	0.012	Low risk (0.053)
					Paralysis	0.29	0.157	70%	0.008	
					Respiratory system harm	0.05	0.027	50%	0.001	
					Skin harm	0.05	0.027	90%	0.002	
					Musculoskeletal injury	0.15	0.081	90%	0.005	
			Asset loss	0.3	Loss of gasifier	0.56	0.168	90%	0.011	
					Loss of pipes and valves	0.32	0.096	90%	0.006	
					Loss of electrical equipments	0.12	0.036	90%	0.002	
			Environmental damage	0.16	Soil pollution	0.22	0.035	50%	0.001	
					Water pollution	0.24	0.038	70%	0.002	
					Air pollution	0.45	0.072	70%	0.004	
					Damage flora and fauna	0.09	0.014	30%	0.000	
Leakage of toxic gases	Toxic gas re-lease throughout gasification.	7%	Health and Safety (H&S)	0.54	Death	0.46	0.248	30%	0.005	Low risk (0.008)
					Respiratory system harm	0.05	0.027	50%	0.001	
			Asset loss	0.3	NA	0	0.000	0%	0.000	
			Environmental damage	0.16	Air pollution	0.45	0.072	30%	0.002	
					Damage flora and fauna	0.09	0.014	2%	0.000	

Figure 6. Extraction of the RAMC risk register.

Table 8. The risk appetite.

Level of Risk	DQLOS Threshold	Response Mechanisums
Extremely high	0.75–1	Cesase the process immediately. Develop sufficient preventions and recoveries.
High	0.5–0.75	Apply treatments as soon as possible.
Moderate	0.25–0.5	Apply treatments within a reasonable time.
Low	0–0.25	No extra treatments needed.

In the current RAMC results shown in Figure 6, all five hazards show low risks; the corresponding DQLOSs are lower than 0.25. This means that the current barriers and design in the plant layout are sufficient to safety. In other higher DQLOS cases, the higher the DQLOS, the riskier the hazard represented. There are several ways for safety practitioners to minimize DQLOS risks. The first is to reduce the frequency of hazard arising. This can be achieved by applying sufficient operational procedures and facility layout. The second is to reduce the likelihood of the consequence arising; this can be achieved by applying sufficient safety barriers, e.g., efficient PPE for occupational safety protection. The third is minimizing the severity of the consequence. This is associated with the inherent safety. In the principle of inherent safety, Kletz indicated (1) to use smaller quantities of hazardous substances in the production, and (2) to replace the hazardous material with a less hazardous substance. Consequently, in an inherent safety system, if an unsafe event arises, the consequence would not be that harmful.

5. Discussion of the Work

5.1. Summary of the Work

The current work has several contributions. Firstly, we have developed a quantitative method, namely RAMC, for assessing the risk of hazards with multidimensional consequences. Many traditional risk assessments make it difficult to devise a scale to measure multidimensional consequences; they are mostly, for example, either health and safety-focused or economic-focused. The application of AHP results in a consistent severity examination which is more reliable than the traditional methods. Secondly, the RAMC algorithm is developed based on the theory of QOL. RAMC offers a novel way for practitioners to measure risk from a health perspective. This provides a solution to a long-lasting issue in risk assessment that considers multiple aspects of consequences of risks. The result of the work is using DQLOS to represent the level of risk, and DQLOS is further used to determine risk priorities. Next, the RAMC delivers a mechanism for professionals to cooperate as a team in assessing the risk of hazards with multidimensional consequences. This is achieved by using the RAMC risk register. The RAMC can be applied at the front end of the safety management process. It potentially benefits the Kaizen system [51] through the Plan-Do-Check-Act (PDCA). It achieves this goal by ensuring the risk of the current system and then supports the practitioners in developing ongoing improvements to minimize the risk.

5.2. Compare RAMC with Conventional Safety Risk Assessment Methods

The RAMC has several strengths compared to conventional safety risk assessment methods. This corresponds to those three weaknesses of conventional methods discussed in Section 2. Firstly, different organizations may have different strategies and requirements in risk management. This further results in different preference criteria among different dimensional consequences. The RAMC has the potential to assist the industry to judge the response criteria by providing a comprehensive risk assessment. This is achieved by employing AHP. In contrast, the traditional methods measure the multidimensional risks in a disjointed way, and they normally weigh different dimensional risks equally. This would result in inefficient risk residual decisions. Secondly, the conventional methods measure the risk of hazards using different measurements—for example, the use of costs in asset loss measurements and the use of QALYs in H&S measurements. All of these measurements have their own scaling thresholds for assessing the severity of consequences and risks. Hence, the risks from different dimensions are incomparable. This further creates difficulties for people to determine which hazard is the most dangerous/risky at the workplace, and further confuses practitioners to develop barriers to prevent the risky hazard. By contrast, the RAMC uses a unified and quantitative indicator, 'DQLOS', to assess the risk of hazards with multidimensional consequences, which can be numerically compared. The normalization in severity scaling is achieved by the weight examination using the AHP method. In the RAMC, weights are used to indicate the severity of consequences that would harm organization safety. The greater weight of a consequence, the greater severity indicator is represented. This unifies the scaling in severity and offers a standard way for risk comparison. The use of the RAMC would be useful in risk identification, and it would further assist in developing risk control priorities.

6. Conclusions

6.1. Conclusion of the Work

The conventional risk assessment methods weakly manage the risk that is associated with the hazards with multidimensional consequences. One of the reasons is the lacking of a solid method in multidimensional consequences scaling. The disjoint measurements in the conventional methods use different indicators to compute risk outcomes and further cause difficulties for practitioners to compare among risks. This is also problematic for practitioners to determine the control priorities and develop safety preventions. To solve the above issues, the RAMC has been developed. Different from the conventional risk computation, the RAMC computes the risk using the QOL theory, and proposes a new risk indicator to represent the potential loss in organization safety, hence DQLOS. The normalization of severity is achieved using the AHP theory. For practical applications, a risk register is also developed. A coal-to-methane gasification case study is addressed to examine the efficacy of RAMC.

6.2. Limitations of RAMC

The AHP may require extensive labor work if it is associated with a large consequence pairwise matrix. We propose that the ontology theory may be helpful to address this issue, as much software, e.g., protégé, is able to be used to address the hierarchy relations between attributes. This is especially useful to address the overlapping relations between parameters, as many AHP studies are facing this complexity.

6.3. Implications for Further Research

The RAMC has been demonstrated in a relatively simple coal-to-methanol gasification case study. The case study delivers a solid framework for the implementation, and also a proof of the RAMC concept. Three main dimensions have been considered in the current work, including loss in H&S, asset loss, and environmental damage, as they are the three major types of harm to the organization. Other dimensional consequences can also be examined using the same method. Alternatively, subdimensional consequences are also considered in the case study, see Figure 5. The considered simple case is developed for the audience to understand the RAMC easily, and although the considered case is simple, many industrial processes can be broken down into such kinds of subsystems. Alternatively, gasification process is a standard process in chemical production; many plants have the process on site, so we think the application of RAMC in this case would be useful for the practitioners to understand the proposed risk theory. The RAMC intended to deliver a quantitative way for safety risk assessment. It particularly contributes to delivering a reliable method that measures the severity of harm in multiple dimensions using AHP. It also examines the organization safety from a health perspective. For its implementation, the methodology requires multiple inputs to measure the likelihood, e.g., using historical data or subjective judgments. Similar to the application of traditional safety assessment, the RAMC requires the cooperation between a number of industry professionals including engineers and H&S representatives. Compared to other measurements, risk computation via DQLOS is relatively simple, this is for the easy adoption for practitioners. The risk register is also developed for practitioners to use at work. The RAMC can be applied to multiple areas from the start of the design process to the end of the operational process. This also assists inherent safety development.

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