Evaluation and comparison of selected methodologies to investigate occupational accidents

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Abstract.
BACKGROUND: The choice of the "right" methodology to carry out the occupational accident investigation process is not an easy task. Each methodology has different conceptual and practical characteristics. The choice will depend to a large extent on the conceptual accident model being used.
OBJECTIVE: The aim of this study has been to evaluate and compare a set of nine methodologies recognised as the most widely used in the field of occupational accident investigation.
METHODS: For this purpose, six evaluation criteria are used which have already been applied and validated by the scientific community with a clear emphasis on the holistic nature of these methodologies.
RESULTS: The results show a detailed analysis of the conceptual, methodological and practical characteristics of the nine selected occupational accident investigation methodologies. The conceptual framework of each of the methodologies, their holistic characteristics in terms of whether they cover the complete information cycle and its possible interrelation, reliability and validity of the methodologies, the experience required for their application, the flexibility in terms of being able to be used in different work environments and finally the ability of the methodology to motivate organisational improvement are presented.
CONCLUSIONS: From this study, it is clear that the analysis of occupational accident investigation it is becoming increasingly necessary to employ scientific methodologies with a clear proactive approach in order to meet the challenges of changing socio-technical systems.

Keywords: Occupational safety and health, occupational accident investigation, evaluation criteria and comparison, holistic approach, Industry 5.0

1. Introduction

The initiation of an investigation of an occupational accident requires a methodology to carry out the entire investigation process, where the correct choice [1, 2] and its scientifically based use structures the investigation process, improves the identification of causes, the interpretation of results and the validity of recommendations [3].

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Initial studies such as the one conducted by Salguero et al. [4] showed that there are not many methodologies available with a specific use in the field of occupational health and safety. The aforementioned research work revealed which scientific methodologies are most commonly used in the field of occupational accident research. At the same time, this review complemented previous reviews [5, 6], which left out of their scope the analysis of occupational accident investigations and methodologies used in favour of risk analysis and assessment in workplaces.

However, the choice of the "right" methodology to carry out the research process is not easy. Each methodology has different conceptual and practical characteristics. Because of this, it will be up to the accident investigator to choose the methodology that best suits the context in it is carried out.

1.1. Conceptual models for occupational accident investigation

The frame of reference is particularly important when conducting an accident investigation [7, 8]. It involves determining how an accident is perceived and, in particular, how the human factor is appreciated to be involved in the accident. This is why the conceptual model of the accident offers a logical way of thinking about how this event occurs.

In this sense, as already stated by Hollnagel [7], all methodologies necessarily involve having a conceptual model of the accident, i.e. a mutually agreed and often non-verbalised understanding of how accidents occur. Therefore, the methodology for occupational accident research must be underpinned by a conceptual framework, which provides the scientific-theoretical model on which the methodology is based; in other words, the choice of methodology will depend to a large extent on the accident investigation model being used [9].

Causality theories and conceptual models of accidents have been developed and described in the literature [7, 8, 10, 11]. The evolution of accident causation models over time shows a shift from the simple sequence of events to the representation of the system as a whole. In parallel, the evolution of accident investigation methodologies reveals a progressive shift from the search for a single immediate cause to the recognition of multiple contributing factors.

Hollnagel [7] presented conceptual models for accident generation classified into four groups as summarised in Table 1:

First is the simple linear or sequential model, represented primarily by the "Domino Theory" proposed by Heinrich [12]. This model describes the accident as the result of a sequence of events in a specific order. Traditional tree techniques are grouped within this model. The sequential model may be attractive because it encourages thinking about causal series, which greatly simplifies and facilitates the task, but it is limited in its ability to explain what happened in more complex systems.

Second is the complex linear or epidemiological model, which describes an accident in analogy to a disease, i.e. as a combination of agents and factors that can generate unfortunate conditions. This model is based on the "Swiss cheese theory" developed by J. Reason [13] in his book Human Error. The epidemiological model provides the elementary consideration of environmental conditions, existing barriers and latent conditions, all of which are determining factors in the accident investigation process.

A third model is the complex non-linear or accident systemic model. This model treats the accident as a probabilistic deviation from normality within the complex system that is the organisation. The systemic model advocates that accidents "emerge" from normality [14].

Table 1
Accident Conceptual models (Adapted from: Hollnagel [7])

	Conceptual model			
	Sequential	Epidemiological	Systemic	Advanced Systemic
Theory	Domino theory [12]	Swiss cheese theory [13]	Normal accident theory [14]	Functional Resonance Theory [7]
Search Principle	Specific causes and well-defined links	Carriers, barriers and latent conditions	Strong couplings and complex interactions	Human variability, technical failures, latent conditions and deteriorated barriers
Model Features	Simple linear	Linear complex	Nonlinear, normal and complex	Nonlinear complex. Normal variability

The culmination of this third generation of conceptual accident models can be found at the present time with the appearance of the concept of Resilience Engineering [15]. This model came about as a result of the collective effort of a group of authors in the field of safety led by Professor Erik Hollnagel, which was followed by a series of publications from 2006 onwards [16]. Resilience Engineering considers that the accident models we used to use were either not true or lacked sufficient veracity in many of the situations in today's environment. Therefore, the view of the accident as a non-linear phenomenon that emerges from a complex system and gives rise to systemic accident models or non-linear models has emerged. Moreover, Resilience Engineering breaks away from the traditional reactive safety concept focused on the study of things that go wrong by analysing simple causal relationships coined with the term Safety I [17]. This is in contrast to the current proactive approach called Safety II, which aims to go further by studying things that go right and day-to-day success through complex, non-linear relationships.

Furthermore, with the recent emergence of Industry 5.0, occupational health and safety is facing a new scenario and paradigm. As the "Industry 5.0" report published by the European Commission [18] argues, new digital and green technologies have the potential to make workplaces more inclusive, resilient and safer for workers. Therefore, new methodologies for workplace accident investigation based on complex adaptive systems will have to be introduced to assess the changing hazards introduced in this new industrial transformation.

1.2. Studies that have analysed and evaluated methodologies for the investigation of occupational accidents

A number of scientific literature review studies have been conducted over the last decades, which have covered the evolution and development of accident investigation methodologies and their comparison [8, 19–25]. These reviews also employed a number of different assessment criteria for the analysis of the methodologies they selected in each of the studies cited.

The results obtained from these studies show the absence of a consensus in the scientific community regarding which methodologies for the investigation of occupational accidents to select and which criteria to define in order to evaluate and compare them. This is why emphasis should be placed on the study by Sgourou et al. [27], which proposed a set of criteria for the evaluation of six scientific methodologies used in the analysis of safety performance in terms of their conceptual, methodological and practical characteristics. The review and evaluation obtained from the study by Sgourou et al. [27] indicated that the proposed criteria could be applied to different types of safety performance assessment methodologies in order to extract useful and suitable information in both academic and professional settings.

1.3. Scope of this research

The safety literature suggests that many safety interventions in this matter are implemented in the sincere hope that they will work, but with a lack of solid evidence of their effectiveness. In this sense, the performance of this study of evaluation and comparison of methodologies in occupational accident investigation is framed within the eight areas of intervention in occupational safety and health recommended by the authors Shannon et al. [28]. The areas are: (a) intervention objectives and their conceptual basis; (b) study design; (c) external validity; (d) outcome measurement; (e) use of qualitative data; (f) threats to internal validity; (g) statistical analysis; and (h) study conclusions. Specifically for the study carried out here, the following areas stand out: a.- in terms of knowledge of the subjective conceptual framework, c.- in terms of the validation of methodologies and h.- in terms of the establishment and study of conclusions.

This is the reason for the present study, which aims to evaluate and compare the conceptual, methodological and practical characteristics of a set of nine methodologies recognised as the most widely used in the field of occupational accident investigation.

After putting the subject matter and objectives into context in the introduction, the rest of the document is structured as follows. Section 2 is devoted to describing the methodology-based approach. In terms of methodology, the evaluation and comparison criteria for the nine selected occupational accident methodologies are detailed. Section 3 presents the results obtained and Section 4 includes the discussion of the main results, ending the article with conclusions and guidelines for future research (Section 5).

2. Methodologies and evaluation criteria

The nine scientific methodologies for the investigation of occupational accidents that have been used

Table 2
Evaluation and validation criteria for occupational accident investigation methodologies (Adapted from: Sgourou et al. [27])

Conceptual and methodological characteristics	1. Theoretical framework	Whether a scientific theory or model supporting the method has been explicitly presented in the literature
	2. Holistic features	Whether the three categories of factors (technical, organisational, human), any relations between them and the relation of the safety management system with the organisation and its external environment have been integrated in the development of the method
	3. Validation	Whether reliability and validity tests of the method have been successfully completed or are in progress
Practical characteristics	4. Required expertise	The required expertise for the implementation of the method and for the analysis of the results
	5. Flexibility	The ability of the method to be used in different work settings
	6. Motivation for improvement	The ability of the method to motivate for improvement

in this evaluation study were extracted from the literature review study by Salguero et al. [4]. This work consisted of a literature review of the main published studies that had analysed a sample of investigated occupational accidents, which in turn had to identify the methodology used in the analysis of these accidents, with a total of 33 different methodologies being identified. In order to assess the importance of these methodologies, an approach based on the analysis of the number of times the selected publications were cited and the impact factor of the journal that published it was used.

In relation to the present evaluation and comparison study, the methodologies selected for this task had to be widely used in practice, well recognised, described in the literature and showing the evolution of accident investigation over time. Some of them, being very young methodologies, may still be relatively undeveloped.

Thus, and as a result of the review of the scientific literature carried out by Salguero et al. [4], a set of nine methodologies were extracted which show versatility in the scope of application, since in addition to being used in accident investigation, they are also used in the analysis and assessment of occupational risks. In other words, these methodologies not only have a reactive approach, dealing with faults and hazards that have already manifested themselves, but also show a proactive approach, i.e. they intervene in safety analysis by identifying risks before allowing an accident to occur. Therefore, by applying the above review strategy, the remaining 24 methodologies were excluded.

Based on these criteria the methodologies selected for evaluation and comparison are: MORT [29], FTA [30], OSHA [31], TRIPOD [32], RCA [33], FRAM [7], HSG245 [34], STAMP [35] and RIAAT [36].

In order to evaluate and compare the selected methodologies for the investigation of occupational accidents, a set of six evaluation criteria is employed as shown in Table 2. These criteria had been proposed by Sgourou et al. [27] for application and validation among six methodologies for safety performance evaluation with a clear emphasis on the holistic nature of these methodologies. The application of these evaluation criteria has been followed up by the scientific community in studies such as Saurin and Júnior [37] on occupational health and safety management systems from the perspective of Resilience Engineering or Griffin et al. [38] on safety management in the oil and gas industry.

It should be added that, unlike the study conducted by Sgourou et al. [27], the nine methodologies selected do constitute an exhaustive review of the literature, in this case in the field of occupational accident investigation. In addition, it should be noted that the selected methodologies are evaluated in relation to the six criteria. All of this is based on information obtained from books, manuals and published studies.

This is why the main novelty and contribution of this study lies in the evaluation and comparison of nine methodologies recognised as the most widely used in the field of occupational accident investigation through the use of six evaluation criteria, which had already been applied and validated by the scientific community.

3. Results

3.1. Analysis of selected methodologies

In the following sections, detailed information is provided on the scope, methodology and objective of the nine selected methodologies for occupational accident investigation. Additional information related to their evaluation and comparison against the six criteria proposed in table 2 is also presented.

3.1.1. Management Oversight and Risk Tree [29]

Johnson developed the Management Oversight and Risk Tree methodology, more commonly known as MORT, in 1973 for the US Atomic Energy Agency. MORT is an analytical procedure for investigating the causes and contributing factors of accidents and incidents.

In MORT, an accident is defined as an unwanted energy transfer due to inadequate energy barriers and/or controls. The methodology follows the concepts of energy transfer and deviation from the systemic conceptual model of accidents [7]. The fact finding aims to identify hazardous forms of energy and deviations from the planned and normal production process.

The MORT diagram employs the logic tree technique with three branches. The branches of the logic tree are safety factors, oversights and omissions, with the accident being the top event. Despite MORT's use of the traditional logic tree of sequential accident causation models, the theoretical model on which the MORT methodology is currently based is the systemic one, as it looks not only at the direct causes of the accident, but also at the causal contributions of management and different levels of the organisation.

It is a methodology that due to its long history has been widely used and validated by public and private agencies in the investigation of accidents in different work environments from the nuclear industry to the oil and gas industries. In this regard, the website of The Noordwijk Risk Initiative Foundation (NRI) with the second version of the MORT user manual [39] is worth mentioning.

As a logic tree methodology, it is simple and does not require a large amount of resources or specialised knowledge to be used. The MORT methodology also provides a comprehensive list of questions to assist the analyst in its use. Its basic structure is flexible and can be modified for use in different sectors. However, the ability of this methodology to motivate organisational improvement is limited.

3.1.2. Fault Tree Analysis [30]

Fault Tree Analysis (FTA) is a methodology used for risk assessment, although it can also be used to determine all possible causes contributing to an undesired event (an accident). This methodology was developed in the 1960s by Bell Laboratories and the Boeing aircraft company [30]. FTA has been applied in the extractive industry, manufacturing industry, power supply, construction and even in studies in health and social services activities.

FTA is a sequential model that shows the various combinations of events through the use of logic gates, equipment failure, human error and work environment factors that can result in an accident. FTA can perform either a qualitative or quantitative analysis or both.

The strengths of this methodology as a qualitative tool are its ability to decompose an accident into its root causes and it is a methodology that has been extensively validated in probabilistic risk assessment in industry. Despite this, FTA is limited in explaining accidents in more complex systems such as the current ones.

As stated by Sklet [21] and Katsakiori et al. [8], FTA is the most widely used of the tree techniques, providing clear step-by-step information for its use. This makes it a methodology that does not require a lot of experience both for its application and for the analysis of the results.

Despite this, FTA is currently in disuse and is considered by authors such as Marhavillas et al. [40] to be exclusively an analysis technique. Aspects such as this explain why its motivation for improvement is insufficient.

3.1.3. Occupational safety and health administration data collection forms [31]

OHSA is the conceptually based, systemic, validated methodology used by the US Department of Labor for investigating accidents in the construction industry.

This methodology identifies the hazards associated with the operation of a system (human errors) such as software, personnel, environment, human-machine interfaces, etc. The method is not limited to hazards to humans, but also to hazards to the system. When OSHA investigates fatal accidents in construction, five categories are used for the grouping of the causes of these accidents, which are: falls from height, electrocutions, struck-by, entrapment and others [41].

OSHA relies primarily on information from employers or media coverage to initiate a fatal investigation. It is used to classify work-related injuries and illnesses and to note the extent and severity of each case.

It identifies and assesses the risks associated with a system's operations through brainstorming and/or checklists. Although the methodology is not very complex, it requires a certain amount of experience in the sector for its application. It is also a methodology used for risk assessment in the food industry, which shows the flexibility of this methodology to be used in different work environments. Safety measures are proposed that favour the ability to motivate organisational improvement. However, this methodology may not be sufficiently valid for complex procedures with multiple error options, so complementary methods should be used for the analysis of the undesired event.

3.1.4. TRIPOD [32]

The TRIPOD methodology was developed in the mid-1990s in a joint project of the Universities of Leiden (Netherlands) and Manchester (UK) for use in the oil industry, but applicable in any type of large organisation.

TRIPOD is based on James Reason's Swiss Cheese epidemiological model. The idea of TRIPOD is that organisational failures are the main factors in accident causation. These factors are more "latent" and, in contributing to an accident, are always followed by a number of technical and human errors. Latent failures are related to eleven Basic Risk Factors.

A failure status profile is constructed, which shows the extent to which general failure types may contribute to future accidents. General failure types are identified through accident investigation and a constructed diagnostic tool. Pre-defined questions and checklist are used.

This method was validated through a computerised version known as TRIPOD-BETA [42], which is a menu-driven tool that guides the investigator through the process of making an electronic representation of the accident.

TRIPOD shows a clear flexibility as it can be used for accident investigations and safety system analysis. However, the method is quite complex and time-consuming to process, and the training course is very necessary for analysts. The TRIPOD methodology was not designed to produce specific recommendations and therefore focuses on non-controllable hazards, and the motivation for improvement is treated as insufficient.

3.1.5. Root Cause Analysis [33]

Root cause analysis (RCA) identifies the underlying deficiencies in a safety management system that, if corrected, would prevent the same and similar accidents from occurring. Root cause analysis is a process based on the sequential model that uses the facts and results of basic analytical techniques to determine the most important reasons for the accident.

Whereas the basic analytical techniques developed until the advent of RCA methodology had to answer the questions of what, when, where, who and how, RCA must be solved by asking why.

The RCA methodology represents the philosophy of single cause, i.e. the belief that there is a single cause for any outcome that, if prevented, would prevent the outcome itself. The problem is that it cannot be confirmed that if the root cause is removed the effects will not happen. The reasoning is that the same effects can be due to different factors, including technical, organisational and human factors.

RCA is widely used in many industries, including health care and quality management (e.g. Ishikawa fish-bone diagrams), which shows the flexibility of this methodology. It is also supported by extensive training material and practical guidance (manuals, etc.). Even so, it does not prevent the necessary experience required for the application of this methodology and the analysis of the results obtained from being necessarily high. It is worth noting that in Spain there is the UNE-EN 62740 Standard of December 2015 "Root Cause Analysis, RCA" [43], through which dense information is provided on how to employ this methodology. Even so, its uptake has not been successful.

It is considered a very efficient method, and since the approach is a simple backward tracing of causes, it is quite robust. The simplicity of the method, however, also means that the search is severely restricted, so the results are limited to the categories defined by the method.

3.1.6. Functional Resonance Accident Model [7]

Functional Resonance Accident Model (FRAM) is a methodology for safety analysis and assessment based on a description of system functions. Based on the complex non-linear conceptual model, FRAM describes the propagation of events using the concept of functional resonance driven by the normal variability of daily system performance. It is therefore, as Le Coze [11] states, the methodological/conceptual approach emerging from Resilience Engineering.

The analysis uncovers dependencies between functions or tasks that are usually missed. It also identifies information needed for the investigation. The concrete result can be a graphical representation of how the accident unfolded and/or a detailed written description.

The method is structurally simple and covers several of the phases of accident investigation. However, it requires a broad and deep initial learning period, due to its different theoretical bases. As the method does not include a classification of accident contributing factors, it is necessary for the user to have extensive experience with the domain of mainly human and organisational factors. FRAM is in turn supported by a software tool called the FRAM visualiser, also complemented by a pocket book for practical use of the method [44].

FRAM is based on a specific theory of functional resonance. This allows it to take non-linear interactions into account and to dispense with the classical cause-effect relationship. The basis for both accident analysis and risk assessment is a description of system functions rather than system structures or components. It is therefore easily scalable.

Although it is a systemic methodology involving complex systems, FRAM has been widely used in areas as varied as aviation, air traffic management, maritime transport, nuclear power plants, railways or health services. However, its use is not as widespread in sectors such as industry or construction. However, a study has recently been published with the application of the FRAM method in the construction sector, which has sought to improve safety management especially in activities for concrete structures [45]. Therefore, not only theoretical but also empirical data are available to support the validation and capacity of this methodology to promote improvement in organisations.

3.1.7. Investigating accidents and incidents, HSG245 [34]

HSG245 was developed in 2004 by the Health and Safety Executive (HSE). It is a manual and methodology created for workers, trade unions, prevention officers and safety professionals. HSG245 was prepared in consultation with industry, trade unions and UK health and safety professional bodies to provide a workbook for employers, trade unions, safety representatives and safety professionals.

It follows Reason's epidemiological causality model of accident causation. The starting point is the event and the method provides fact-finding aids with specific structured questions. The aim of the analysis is to state the reasons why this happened and to find immediate, underlying and root causes. A checklist with underlying and root causes is also provided.

It is therefore a methodology that has been thoroughly validated by the UK's non-departmental public health and safety agency. However, despite the numerous manuals and guides published by the Health and Safety Executive (HSE), the use of this methodology in accident investigation requires analysts with extensive experience in this technique.

HSG245 offers significant potential for improvement, through the corrective actions that are indicated after the completion of the accident investigation. However, the objective of this methodology does not focus on the risk assessment of the analysed organisation.

3.1.8. Systems-Theoric Accident Model and Processes [35]

Systems-Theoretic Accident Model and Processes (STAMP) was proposed by Leveson in 2004 in his study entitled "A New Accident Model for Engineering Safer Systems". It is a method based on the Accimap method [46], which classifies accidents as the result of inadequate safety control. Accidents occur when component failures and inappropriate interactions between system components are not under control. This method describes various forms of control, such as managerial, organisational, physical, operational and production-based controls.

STAMP is based on the systemic conceptual model of causality that extends the traditional epidemiological model to include technical and social contributing factors and their relationships. To support the identification of control failures, Leveson proposed a classification of control failures that includes: inadequate control of actions, inadequate execution of control actions and inadequate or non-existent feedback. Thus, the analysis of an accident with the application of the STAMP method describes failures throughout the entire control structure of the system leading to the accident. Early versions of this methodology even analysed software errors.

STAMP has been extensively validated in multiple industry sectors successfully. Application areas have included aviation, air traffic control, space, defence, automotive, railways, chemicals, oil, gas, medical devices, healthcare and workplace safety, with growing interest coming from new areas such as the pharmaceutical industry and the finance and insurance sectors [47–49].

It is a time-consuming methodology that is relatively difficult to assimilate. It can be used at various levels of the system. Probabilities of failure can be calculated, making it a direct monitoring method.

The motivational potential for organisational improvement can be identified in the broad sectors in which STAMP has been validated. However, its use as a risk assessment tool for benchmarking purposes is not so recognised, and no evidence of its implementation has been found.

3.1.9. The recording, investigation and analysis at work [36]

RIAAT (The Recording, Investigation and Analysis of Accidents at Work process), was conceived to analyse the complete cycle of the accident at work with the aim of contributing to the improvement of the effectiveness of prevention. Hence the holistic approach recognised in this methodology. The process covers the complete accident information cycle by recording the event and its main circumstances; conducting an investigation and causal analysis in a multi-layered manner; producing a plan of action; and establishing the necessary activities to share information and promote organisational learning

RIAAT offers a systematic, structured and easy to apply model, even for "non-experts". This methodology is based on the theoretical models of "accident organisation" proposed by Reason [50] and "human error" by Hollnagel [51]. A particularly important aspect of this method is that it already incorporates the variables proposed by Eurostat [26].

The RIAAT method comprises five phases grouped around two main stages. The first stage is a simplified investigation process that covers the legal reporting requirements and focuses on the analysis of the immediate causes and circumstances, i.e. the most "observable" elements of what has happened. The second stage is an in-depth analysis, or full investigation, in which other possible weaknesses and conditions within the organisation are identified and analysed. This second stage not only goes beyond existing legal obligations, but aims to provide organisations with a structured tool for identifying opportunities to improve their safety practices and policies, regardless of whether or not they have a formal safety management system. This methodology has a section where the risk assessment of the investigated organisation is verified and reviewed, but RIAAT is not used as a methodology for conducting this type of assessment.

RIAAT was validated by the Portuguese government as a reference methodology for the investigation of occupational accidents in Portugal through the CAPTAR "Learn to prevent" project, and a user manual has been available since 2010. Likewise, the degree of versatility of RIAAT is recognised by its capacity to be used in different work environments as shown in the publications by Cordeiro et al. [52]; Costa et al. [53]; da Fonseca et al. [54].

4. Evaluation, comparison and discussion of selected methodologies

The results of the evaluation and comparison of the nine methodologies for the investigation of occupational accidents are shown in table 3 and have been synthesised and discussed in the following paragraphs.

Among the conceptual and methodological features evaluated, the nine methodologies for occupational accident research that have been analysed, as expected, have a conceptual model as a "theoretical background". As already advanced by Hollnagel [7] and Katsakiori et al. [8] it is not only useful but also necessary to know which accident model is behind the description, since this determines both the principles of the search and the objectives of the analysis. However, even if the conceptual frame of reference is essential to understand the accident, as Le Coze [11] argues, the question arises whether the "old" models are still useful or whether new and innovative models should be used for the new times. In this sense, the advanced systemic model represented by Resilience Engineering is certainly innovative as well as promising [55]. Even so, within the new industrial environments associated with Industry 5.0, colloquial accidents will continue to occur and can still be investigated with traditional conceptual models.

As can be seen from table 3, methodologies based on conceptual models that are clearly no longer used by the scientific community, such as FTA and RCA, whose frame of reference is the sequential model, currently exist and are widely used. Similarly, TRIPOD and HSG245 methodologies with the epidemiological model as their theoretical framework are also widely used. The sequential and epidemiological models conceive the accident as a simple combination of concatenated errors/failures that are always avoidable. Very remarkable is the FRAM methodology, which uses an advanced systemic model based on the concepts and theories of Functional Resonance, which is the conceptual model that best responds to today's changing reality. FRAM and Resilience Engineering [15] are today the ideal model-methodology tandem for understanding the limits of variability and normal performance and, therefore, improving health and safety management in organisations. We could even be talking about the first proactive or leading

Table 3
Results of evaluation of methodologies for occcupational accidents investigation

Assessment criteria	MORT	FTA	OSHA	TRIPOD	RCA	FRAM	HSG245	STAMP	RIAAT
1.- Theoretical framework	Yes, Systemic Model	Yes, Sequential Model	Yes, Systemic Model	Yes, Epidemiological Model	Yes, Sequential Model	Yes, Advanced Systemic Model	Yes, Epidemiological Model	Yes, Systemic Model	Yes, Epidemiological-Systemic Model
2.- Holistic features	Technical, organisational and human factors	Technical, organisational and human factors	Technical, organisational and human factors and their inter-relations	Technical, organisational and human factors	Technical, organisational and human factors	Technical, organisational and human factors and their inter-relations	Technical, organisational and human factors	Technical, organisational and human factors and their inter-relations	Technical, organisational and human factors
3.- Validation	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory	To be proven	Satisfactory	Satisfactory	Satisfactory
4.- Required expertise	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No
5.- Flexibility	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes
6.- Motivation for improvement	No	No	Yes Potential motivation for improvement	No	No	Yes Potential motivation for improvement	Yes Potential motivation for improvement	Yes Potential motivation for improvement	Yes Potential motivation for improvement

conceptual model and methodology with the ability to anticipate future developments and thus be able to predict an accident [56].

The holistic characteristics of each of the nine methodologies evaluated were examined by reviewing their theoretical background and their evaluation elements. It was found that only OHSA, FRAM and STAMP integrate and interrelate the three groups of factors (technical, organisational and human) with the organisation and its working environment. This aspect shows that contrary to what Rasmussen [46] argues, not all methodologies for occupational accident investigation show a holistic approach to accident causation and its relation to safety management and, consequently, the assessment of safety performance.

As far as validation is concerned, as Trochim [57] states, it is a basic requirement for the development of any scientific methodology. Among the practical characteristics of the nine methodologies evaluated, the criterion of "validation" was analysed on the basis of different published reliability tests of the methodologies selected for evaluation. All methodologies have been satisfactorily validated in different fields of application in occupational safety and health. For methods such as FRAM, there are still not many results available on their validity and reliability in occupational safety and health. This may be due to the fact that it is a model with a relatively short participation in the scientific literature in the field of small and medium-sized enterprises.

Three of the methodologies evaluated (MORT, FTA and RIAAT) show that they do not require special expertise for their application and analysis of the results obtained from their use, i.e. these three methodologies can be put into practice without any expert knowledge in the field.

With the exception of STAMP and HSG245, the rest of the methodologies show adequate "flexibility", given their ability to be used in different work environments. While methodologies such as OSHA have been designed for use in construction, methodologies such as FTA have been applied in different work activities such as extractive industry, manufacturing industry, power supply, construction and even in studies in health and social services activities. This result in itself confirms the hypothesis of Katsakiori et al. [8] that a "good" research method must take into account the specific context of the accident.

On the other hand, addressing the concept of "versatility" beyond the concept of "flexibility", it should be noted that methodologies such as MORT and HSG245 only have a reactive approach, dealing with failures and hazards that have already manifested themselves, while the rest also manifest a proactive approach, i.e. they intervene in the safety analysis by identifying risks before allowing an accident to occur.

In terms of "motivation for improvement", the STAMP, OSHA, HSG245 and RIAAT methodologies were found to offer potential motivation for improvement in the organisations where they are used. Methodologies such as MORT, FTA, TRIPOD and RCA, whose design was based on the use of tools such as the logic tree, do not offer the motivation for improvement that is required. As for the FRAM methodology, studies such as Pardo-Ferreira et al. [45] argue that safety management on construction sites could be improved from a "what goes well" perspective.

5. Conclusions

The aim of this study has been to evaluate and compare a set of nine methodologies recognised as the most widely used in the field of occupational accident investigation, which in turn have been used in the scientific literature or by international public agencies and institutions.

By analysing the nine methodologies selected in this study on the basis of the evaluation criteria that had already been validated, the aim was not to see which methodology is the best, but to distinguish the extent to which they meet both the conceptual and practical criteria. Similarly, the aim is to find out which of these methodologies are adapted to the new times in terms of being based on a non-linear systemic conceptual model of safety, which pays special attention to the monitoring of the normal variability of organisations.

As a result of the evaluation of these nine methodologies, we conclude that it is necessary to employ in the analysis of accidents at work validated scientific methodologies that show in addition to the classic reactive approach associated with retrospective indicators or also called lagging indicators, those with a prospective vision with the use of leading indicators, which provide a forecast of future performance. Ultimately, it will be indispensable that methodologies for the investigation of occupational accidents, reactive in nature by definition, employ techniques combined with risk assessment methodologies.

We find ourselves at a decisive moment, in which some of the "old normal" will crumble and a "new normal" will emerge. This transition could be a window of opportunity for us to actively shape and renew the role of industry in society. This will require a proactive, purpose-oriented approach to sustainability, health and safety of businesses and workers, rethinking the paradigms underlying our understanding of how societies, economies and industries function.

Finally, as a limitation of the study, the evaluation of the nine methodologies for the investigation of occupational accidents selected from the review by Salguero et al. [4] was based solely and exclusively on data extracted from the review of published material. Even so, we understand that these restrictions could be overcome with the direct collaboration of the authors or researchers of these methodologies for the investigation of occupational accidents.

Ethics statement

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki.

Conflict of interest

No potential conflict of interest was reported by the authors.

Conflict of interest

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

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