The evaluation of common contemporary occupational accident models using two accident investigations

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ABSTRACT

The purpose of this paper is to compare three contemporary accident causation models, namely the Swiss Cheese, HFACS, and Fu (2018) Model-based on two accidents existing in the literature. The accidents reviewed are a mine explosion accident and an electrical plant accident. In this way, the validity of the models can be evaluated and weaknesses and strengths revealed. This study discussed the advantages and possible limitations of these models, and according to this discussion, all these models include human and organizational factors and have been found scientific and systematic. According to the results, Fu (2018) and HFACS are more modern, since they were developed based on Swiss Cheese. The product of this research will be a recommendation for safety investigators and accident inspectors which way to turn when choosing the most applicable accident analysis method.

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Introduction

An accident is an ill-fated event that happens suddenly and involuntarily which, frequently resulting in a casualty or an injury. Due to unfavourable work conditions, workplaces are one of the riskiest places in terms of accidents. As a result, there are various occupational accident definitions. According to the Occupational Health and Safety Law No. 6331, an occupational accident is defined as any occurrence taking place at the workplace or due to the performance of work which leads to death or physical or mental impairment to the physical integrity of the victim. "In order to prevent any kind of accident it is highly recommended to identify all causes that contribute to accidents. Since occupational safety and health has been source of major global concern, safety researches are focused on accidents and various accident causation models that have been developed by investigators. Accident causation models seek to lead us to answers to two basic questions: (i) Why do accidents happen? (ii) How do accidents happen?"

Theoretical structure for retrospective analysis of accidents and prospective characterisation of risks is the reason why accident causation models are created and used (Arboleda & Abraham, 2004). Different perceptions of the accident process led to the development of different accident causation models (Mitropoulos et al., 2005).

According to depth analysis accident causation models can be labelled as classical, modern and contemporary. Early models were more focused on the effects of personnel causes called unsafe acts and unsafe conditions at the workplace as main reason of accidents. Since they are often descriptive models, and are not predictive, they are not usually effective for accident prevention (Rathnayaka et al., 2011). Accident Proneness Theory and Domino Theory are among the best-known classical accident models. Modern accident causation models add education and management factors as the fundamental cause of human factors (Fu, Cao, et al., 2017). Contemporary accident causation models propose that latent failures can be much more effective for accidents like defects in safety management system and those in safety culture.

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In this study, three contemporary models, namely Swiss Cheese, HFACS, and Fu(2018), were used to study two well-known accidents from the literature, the mine explosion accident and an electrical plant accident. This paper provides a comparison of these models and suggestions for safety investigators and accident analysts to be used in various aspects of occupational accident researches.

Literature Review

Conceptual Background

The Swiss Cheese Model

Reason has developed the Swiss Cheese Model in order to show how personnel and supervisory factors affect the accident mechanism (Reason, 1990). The air transport sector uses still this model in order to prevent personnel errors (Shappell & Wiegmann, 2000). Since active and latent conditions, failures are depicted holes in a Swiss cheese slice, the model is named „Swiss Cheese Model“. Latent conditions are considered to be accident triggers. The Swiss Cheese Model proposes a model that tracks accident causation at different levels of the organization. In this model there are consecutive safety blockade (descriptive slices). When one of these blockades fails, they drill into the next slice. When there are failures across all the slices, all the descriptive holes line up and lead to an accident. But holes in the model are not static. Depending on the state of the system, they can move on the slices, new holes can be drilled or some holes may be closed and they can constantly change their size (Figure 1).

According to Sidney Dekker, the researcher's aim is to find the location, type and size of each hole and identify the reason for these changes (Dekker, 2002). Short-term gaps can be created by operators' violations and errors. However, longer and more dangerous holes occur as a result of the decisions of designers, builders, maintainers and senior managers. These are referred to as latent conditions instead of latent failures or latent errors. A condition does not provoke an incident, but it must exist in order for the element of the cause to have an outcome. For example, Oxygen is required for a flame, but the source of fire is the cause of the accident. The usage of this term demonstrates that all high-level decisions place pathogens into the system. The existence of latent conditions is common for all organizations regardless of accident records (Hollnagel, 1998). According to the Swiss Cheese Model, front-line operators are not the only ones responsible for accidents, and an accident can occur simply as a result of the combination of events and conditions. Because of this fact, this model has been mostly used in occupational accidents (Kujath et al., 2010).

Figure 1: The Swiss Cheese Model – Current Model (Hollnagel, 1998)

Unlike this last version of the Swiss Cheese Model, where the layers are not labeled, the previous version of the model consists of five layers (Reason, 1990) (Figure 2):

Senior Management Fallible Decisions: Wrong decisions made by senior managers/designers/management

Line Management Deficiencies: Deficiencies in management levels resulted from wrong decisions (e.g. lack of education).

Precursors of Unsafe Acts: Unsafe conditions that cause a wide range of unsafe acts (e.g. not using personal protective equipment).

Unsafe Acts: A mistake or a violation

Inadequate Defenses: Lack of system defenses that trigger accidents (e.g. protection measures from direct contact with dangerous substances).

Figure 2: The Swiss Cheese Model – Version I (Hollnagel, 1998)

The Human Factors Analysis and Classification System (HFACS)

HFACS is an accident causation model developed to investigate the personnel factor in military aircraft accidents. It was suggested by Shappell and Wiegmann in 2000 (Shappell & Wiegmann, 2000) and is based on the Swiss Cheese Model. Reason's theory is applied by the structure of HFACS. Swiss Cheese contains only a few small details on how to be adapted to real life, thus remaining mostly a theoretical study. In other words, the holes in the cheese are not defined what they really are. The purpose of HFACS is to describe the "holes in the cheese". For this reason, it was developed using more than 300 naval aircraft accidents. HFACS identifies the four levels found in Reason's model: Unsafe acts, Preconditions for unsafe acts, Unsafe supervision, and Organizational influences (Figure 3).

Figure 3: Swiss Cheese Model modified from Reason (1990) (Shappell and Wiegmann 2000)

Two categories have been created for unsafe acts: errors and violations (Reason, 1990) (Figure 4). Errors can be specified as cognitive and physical activities that prevent a person from performing an intended act. Violations mean deliberately neglecting the rules and regulations set for safety. Errors are further subdivided into three categories: skill-based errors, decision errors and perceptual errors. Skill-based errors are mistakes caused by distraction and forgetfulness like omission or confusion of some procedural steps, forgetting some items in the checklist, losing control, and other errors caused by distraction and forgetfulness. Decision errors represent deliberate actions, but the decision or the implemented plan is either inappropriate or insufficient for the current situation. Even though a person made the wrong choice, decision errors are due to good intentions often accepted as "forgivable mistakes". Perceptual errors refer to errors caused by a person's perception. If a person's perception of the world is different from the reality, it is almost certain that such person will make a mistake.

Violations are classified into two categories: routine violations and exceptional violations. Routine violations are actions and behaviors that are a habit and tolerated by the management, but are against rules and regulations (Reason, 1990). Unlike routine violations, exceptional violations are not a person's habit and are not tolerated by management. Preconditions for unsafe acts include three categories (Figure 4): environmental factors, condition of operators, and personnel factors. The subcategories adverse mental states, adverse physiological states, and physical/mental limitations (visual limitation) have been identified for conditions of operators. Being mentally ready or not to perform a job is one of the most significant causes affecting performance in all sectors. The adverse mental states subcategory was created to explain such mental states. Adverse physiological states category represents to medicinal or physiologic states that prevent safe performance of a job. Factors such as medical illness and physiological incapacitation that negatively affect performance can be counted as adverse physiological states. The physical/mental limitations category is created for situations when operational requirements exceed the person's mental or physical capacity. For example, humans have a very limited night vision. The personnel factors category includes crew resource management factors and personal readiness factors (e.g. excessive physical training, self-medicating). The crew resource management category was generated to explain the lack of coordination among the staff. In all sectors, the employee is expected to perform at an optimum level. Personal readiness category is interrupted if a person does not prepare himself physically and mentally for his tasks.

In addition to human factors, environmental factors can cause operators to act in an unsafe manner. These environmental factors include two categories: physical environment and technological environment. Physical environment means both the work setting (e.g. air, altitude, terrain) and conditions such as heat, vibration, lighting, toxins, etc. Technological environment on the other hand covers various areas such as equipment and controls design, display/interface features, checklist layouts, task factors, and automation. (Wiegmann & Shappell, 2017).

Four categories have been identified for unsafe supervision (Figure 4): inadequate supervision, planned inappropriate operations, failure to correct the problem, supervisory violations. Inadequate supervision takes into account cases such as improper supervision (e.g. failed to provide training and correct data). Planned inappropriate operations represent cases like when enough rest time is not provided, work pace and shift hours put personnel at unacceptable risk since performance is negatively affected. Failure to correct problem category includes problems like personnel, training, equipment and safety, which are known to the management but are not resolved. The category of supervisory violations is created for cases where rules and regulations are even deliberately neglected by supervisors. However, it is much less common for supervisors to violate their principles and rules while managing their own assets. An example of this category is hiring an operator without a license. The wrong decisions of the upper management precisely affect administrative proceedings, and activities and states of operators. Unfortunately, these kinds of supervisory factors cannot often noticed by safety professionals. Three categories have been identified for organizational influences (Figure 4): resource management, organizational climate and operational processes. Resource management classification covers areas such as decision making at the corporate level, allotment and regulation of administrative resources like personnel assets and financial resources, and materials/plants. Organizational climate represents a wide range of supervisory variables that affect employee productivity. Generally, organizational climate is seen as the working environment of the organization. An indicator of organizational climate is the system of business organization (chain of command, distribution of authority and responsibility, communication channels, etc.). The category of operational processes contains corporate decisions and rules governing daily activities within an organization. For example, aspects such as work pace, time pressure or work schedule can negatively affect safety.

Figure 4: The Human Factors Analysis and Classification System (HFACS) (Shappell & Wiegmann, 2000)

As a result, the HFACS framework has been developed to fill the gaps between theory and practice and provide a comprehensive and useful tool for researchers to describe and categorize personnel factors of aircraft accidents. The model, which is created using Reason's model of latent and active failures, includes all human factors, conditions of operators and organizational impacts. HFACS has been used for roughly 1,000 military aviation casualties and the accuracy and efficacy of HFACS has been tested over and over again (Shappell & Wiegmann, 2000).

Fu (2018) Model

The Fu(2018) Model (Fu et al., 2018; Fu, Fan, et al., 2017) proposed by Gui Fu is an updated version of 24Model that emphasizes how supervisory and personnel factors affect accidents. This new model includes all the basic features of 24Model with significant improvements to 24Model (see Figure 5). Fu Model is classified into two main categories, namely internal causes and external causes. Five subcategories, which are unsafe acts, unsafe conditions, flaws in safety knowledge, safety awareness and safety habits, deficiencies in safety management system, and deficiencies in safety culture have been created for the internal causes.

Figure 5: Fu(2018) Model (Fu et al., 2018)

'Unsafe acts' includes actions that cause an accident. According to Fu Model there are two kinds of unsafe acts: a fault made inadvertently or negligence of a rule or regulation. 'Unsafe conditions' represents conditions which seriously influence an accident. There are factors connecting unsafe acts and unsafe conditions. In other words, unsafe acts can trigger unsafe conditions, or vice versa unsafe conditions can trigger unsafe acts, or both can cause the accident directly. The category of 'Flaws in safety knowledge, safety awareness, safety habits' contains indirect causes that are intently related to direct causes. 'Deficiencies in safety management system' represents weaknesses in safety policy, safety procedure and the structure of safety management of an organization. 'Deficiencies in safety culture' means inadequate safety culture, which combines values, ideologies, and attitudes of the entire organization. 'External causes' includes all factors outside the organizations that have an impact on the occurrence of an accident such as top management, suppliers, family members or social environment.

The right-side arrows show how internal causes lead to a casualty. This sequence starts with flaws in the safety culture of the organization, follows to the deficiencies in the safety management system, the shortcomings in safety knowledge and awareness, on to unsafe acts and unsafe conditions and ultimately ends with an accident. Arrows directed to the left side illustrate the accident investigation steps. The accident analysis starts after an accident happens. Unsafe acts and unsafe conditions are studied first, followed respectively by weaknesses in individual's safety knowledge and awareness, flaws in safety management system, and finally deficiencies in safety culture. For the safety culture category Fu has created an extensive list of 32 items, which identify defects and faults in the safety culture (Table 1). After the examination of internal causes is carried out, external factors affecting the accident are then examined.

Table 1: Safety Culture Elements (He et al., 2012)

No	Key Element	No	Key Element
1	Safety Importance	17	Safety council demands
2	All accidents preventable	18	Formation of the way of safety system
3	Safety creates economic benefits	19	Safety procedure implementation methods
4	Safety integrated into management	20	Types of investigated accidents
5	Safety depends on safety awareness	21	Types of safety check
6	Safety responsibility	22	Caring for injured workers
7	Awareness of safety investment	23	Amateur safety management
8	Role of safety regulations	24	Treatment of safety performance
9	Safety values formation level	25	Facilities satisfaction
10	Degree of leaders' responsibility	26	Mastering of Safety performance
11	Role of safety department	27	Safety performance and human resources
12	Employee participation in safety	28	Safety management of subsidiary and co-firms
13	Safety training requirements	29	Function of safety organization
14	Degree of the department's safety responsibility	30	Work of safety department
15	Effects of community safety	31	Overall safety expectations
16	Function of safety management system	32	Emergency response capabilities

In order to compare the three models two accidents published in literature were chosen, one is a mine explosion accident and the other one is an electrical plant accident. The advantages and weaknesses of the models were determined from the results of the comparison. The accidents scenarios and comparison tables are provided as illustrated below (Table 2-3).

The mine explosion accident

The gas concentration at the tunneling face is monitored by the controller on duty, and when it increased to 1.21%, the controller immediately informed mine management. However, the gas inspector on duty was not certified for his job and thus unaware that

workers must immediately be evacuated when the gas concentration rises above 1.0%. Because of his lack of knowledge, the works was not stopped nor were the workers evacuated, and tunneling of the tunnel using the tunneling machine continued despite the explosion warning. The Team Leader then noticed that flaking of the ribs was the cause of the gas concentration increase. The gas alarm recognized dangerous gas levels and sounded off above the ground three times, which the dispatcher in on duty reported as prescribed by the procedures. Regardless of all of the steps taken, the mine persons in charge at the mine did not deem this incident as significant, and the result was a blast killing 10 workers (Fu, Cao, et al., 2017).

Table 2: Causation Analysis of the mine explosion accident

Axioms	HFACS	Fu (2018)	Swiss Cheese
After the explosion alert, the tunnel was excavated using the drilling machine.	Exceptional violation	Deficiencies in safety culture (R1) Flaws in safety knowledge, safety awareness, safety habits (R2) Unsafe Acts (R3) (R1→R2→R3)	Unsafe act
The work was not stopped when the gas concentration occurred.	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Line management deficiencies
Workers were not evacuated when the gas concentration increased.	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Line management deficiencies
Test spots in the complex geological tectonic belt were not increased when the explosion prevention effect was controlled (only 5 test spots).	Failure to correct problem	Deficiencies in safety culture (R1) Flaws in safety knowledge, safety awareness, safety habits (R2) Unsafe Acts (R3) (R1→R2→R3)	Line management deficiencies
The approval of gas drain holes did not completely comply with regulations (some drilling holes did not fit the model).	Exceptional violation	Deficiencies in safety culture (R1) Flaws in safety knowledge, safety awareness, safety habits (R2) Unsafe Acts (R3) (R1→R2→R3)	Unsafe act
Hydraulic cracking was carried out during tunneling.	Planned inappropriate operations	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Line management deficiencies
The construction process was violated using hydraulic cracking technology.	Planned inappropriate operations	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Line management deficiencies
The coal mine manager failed to examine the gas explosion prevention measures at monthly and quarterly intervals.	Inadequate supervision	Deficiencies in safety culture (R1) Flaws in safety knowledge, safety awareness, safety habits (R2) Unsafe Acts (R3) (R1→R2→R3)	Line management deficiencies
A large number of methane detectors were installed improperly.	Routine violation	Deficiencies in safety culture (R1) Flaws in safety knowledge, safety awareness, safety habits (R2) Unsafe Acts (R3) (R1→R2→R3)	Unsafe act
Two workers used each other's cards to register and management did not stop this violation.	Supervisory violation	Deficiencies in safety culture (R1) Flaws in safety knowledge, safety awareness, safety habits (R2) Unsafe Acts (R3) (R1→R2→R3)	Line management deficiencies

Table Cont'd

Although the changing geological conditions are known, explosion prevention measures were not supported and the work continued.	Failure to correct problem	Deficiencies in safety culture (R1) Flaws in safety knowledge, safety awareness, safety habits (R2) Unsafe Acts (R3) (R1→R2→R3)	Line management deficiencies
The gas controller was not certified and experienced.	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Line management deficiencies
The working face was folded leading to changes in coal seam thickness.	Physical environment	Unsafe Conditions	Precursors of unsafe acts
Rib flaking was the reason for gas concentration increase.	Physical environment	Unsafe Conditions	Precursors of unsafe acts
Inexperienced workers were employed in underground coal mines.	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Conditions (R4) (R1→R2→R3→R4)	Line management deficiencies
Many important operators were not certified.	Resource management	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Conditions (R4) (R1→R2→R3→R4)	Senior management fallible decisions
The gas inspector was unaware that workers must be evacuated when gas concentration rises above 1.0%.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act
Although it was realized that gas concentration exceeded the limit it was not responded to this issue.	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Line management deficiencies
The limits for gas concentration limits were not graded correctly, which lead to the lack of a rule to evacuate staff immediately when the gas concentration exceeds the limits.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
Company senior management did not ensure that workers were evacuated promptly after being notified that the gas concentration exceeded limits.	-	External Causes	-
Specific approvals for facial explosion prevention design, regional explosion prevention measures and assessment report were not compliant.	-	External Causes	-
The firm failed to carry out a training on safety and applicability of the hydraulic cracking technology.	-	External Causes	-

An electrical plant accident

There was a blast at the high pressure steam pipeline at Dangyang Power Plant. One day prior to explosion, one person suffered foot injury from the steam leaking out of the pipeline. The leakage was reported to the managers by the operators, but this did not lead to cure or reparation measures and the plant continued operating as usual. The leakage at the steam pipeline was not cured the following

day neither nor were the prevention steps taken and leakage was worsening. The plant continued its operation until the blowout of the steam pipeline in the afternoon hours, killing 22 people and injuring four, along with serious casualties to the buildings (Fu et al., 2018).

Table 3: Causation Analysis of the electrical plant accident

Axioms	HFACS	Fu(2018)	Swiss Cheese
Procurement officers did not check the quality certification of the flowmeter supplied by the producer.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Unsafe act
Procurement officers did not check the quality of the flowmeter before installation.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Unsafe act
The personnel started using the flowmeter on their own.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Unsafe act
Operators and managers did not take effective measures to control the steam leak.	Exceptional and supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe Acts (R4) (R1→R2→R3→R4)	Unsafe act ve line management deficiencies
Managers ignored the accident that caused a foot injury on the day the steam started leaking.	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe conditions (R4) Unsafe acts (R5) (R1→R2→R3→R4) ↘R5	Unsafe act
The thickness of the weld in the flowmeter did not comply with technical standards.	Technological environment	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe conditions (R4) (R1→R2→R3→R4)	Precursors of unsafe acts
The central control room was right next to the steam pipeline.	Physical environment	External Factors (R1) Deficiencies in safety culture (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe conditions (R4) (R1) (R2→R3→R4)	Precursors of unsafe acts
The central control room and the steam pipeline were separated from each other only by double-pane glass.	Physical environment	External Factors (R1) Deficiencies in safety culture (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe conditions (R4) (R1) (R2→R3→R4)	Precursors of unsafe acts
Senior management did not order the organizations to examine the drawings of the design and detect possible design errors before starting construction of the building .	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe conditions (R4) (R1→R2→R3→R4)	Unsafe act
Procurement officers were unaware of the consequences caused by violating supply management requirements.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act

Table Cont'd

The personnel were not aware the requirements in technical standards.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act
The personnel did not know the importance of following requirements for the installation in the OHS management system	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act
The personnel were incapable to detect the risks related to the steam leak.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act
Staff was not familiar with the results caused by the failure to take the necessary measures to control the cracked pipeline.	Exceptional violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act
The personnel did not have the habit of controlling dangerous situations and prompt investigation of the causes of an accident.	Routine violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act
Senior management was unaware of the consequences of not examining design drawings.	Supervisory violation	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Unsafe act
There was no commissioning procedure in place for the flowmeter.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
Steps for the implementation of commissioning were not defined and there was lack of access to technical standards requiring that prior to use, the procured equipment must be checked.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
The organization lacked a process to control the quality of procured equipment.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
There were no processes in place to identify the danger of hot steam leakage from a substandard flowmeter.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
There were no processes in place to determine the risks associated with the implementation of supply management in the OHS management system.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
There were no training programs aimed at informing and raising the awareness of the personnel on technical standards and supply management requirements, equipment quality control, and equipment commissioning.	Resource management	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) Unsafe conditions (R4) (R1→R2→R3→R4)	Senior management fallible decisions
There were no processes in place to monitor the implementation of procurement management and commissioning procedure.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions

Table Cont'd

There were no programs to check whether all elements in the OHS management system were effectively and adequately implemented.	Inadequate supervision	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Line management deficiencies
There was a lack of training programs aimed at informing personnel and raising their awareness about what steps to take case of a cracked pipeline and how to detect possible steam leakage.	Resource management	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
Top management failed to take overall responsibility for the protection of the operational safety thus demonstrating leadership and commitment to their employees. .	Inadequate supervision	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Line management deficiencies
Protection of operational safety was not clearly defined and responsibilities are not clearly assigned across all levels within the organization.	Organizational climate	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
Upon steam leak occurrence, an accident management process has not been established to investigate the causes and take necessary measures.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
There were no processes aimed at identification of risks due to design deficiencies.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
There were no defined processes of access to current technical standards for joint review of design drawings.	Operational processes	Deficiencies in safety culture (R1) Deficiencies in safety management system (R2) Flaws in safety knowledge, safety awareness, safety habits (R3) (R1→R2→R3)	Senior management fallible decisions
Designers failed to follow the requirements defined by the technical standards	-	External Causes	-
External pressure was created when the heat and electricity obtained during the trial operation were sent to one of the investors.	-	External Causes	-

Implications

When comparing the tables of the two accidents analyzed here, it is easily observed that the three contemporary accident causation models include both human and organizational factors, and they were successful in evaluating the accidents. However, all three models above have certain advantages and limitations.

The analysis process of these three models is relatively simple and easy to understand. Their step-by-step structure increases their usability and reliability. This is one of the main reasons for choosing these models in this study. Furthermore since all of these three models are modular, this feature prevents wasting time. This structure enables any user to arrive at similar results. However, the difference is that Fu(2018) and Swiss Cheese models do not identify types of the unsafe acts, where HFACS specifies whether an unsafe act is an error or a violation. If it is an error, it clarifies the type of the error. If it is a violation, it indicates whether it is a supervisory or personnel violation, and also identifies routine or exceptional violation. In addition, while Fu Model and Swiss Cheese are identifying many actions as unsafe acts, HFACS classifies them as “failure to correct problem”, “planned inappropriate operations”, etc. Since it is much simpler to perform detection and prevention of unsafe acts through this classification, HFACS is more successful in this regard. In HFACS, psychological and physiological factors can be determined through interviews with personnel. Fu(2018) and Swiss Cheese models do not have such a category. HFACS requires very detailed data (Lenné et al., 2012) compared to Swiss Cheese or Fu(2018) models. Notice that HFACS Framework has 19 subcategories about which accident reports contain less information. Another drawback of using HFACS is the requirement of a more intense expert knowledge than for Fu and Swiss Cheese models due to its highly detailed categorization (Li, Harris, Yu, 2008). Nevertheless, since HFACS was proposed for

the purpose of analyzing the causes of aircraft accidents, the “team resource management” category could not be applied to the accidents evaluated above. Therefore, when both HFACS and Swiss Cheese are applied to a non-aviation field, they have to be modified according to the conditions of that area (Fu, Cao, et al., 2017). Besides that, the category of external factors is not included in HFACS and Swiss Cheese and therefore the causes outside of the organization could not be detected, although this category is essential in order to detect all causes of accidents.

Swiss Cheese and Fu models are simple and easy to apply. They offer the opportunity to work with limited accident data because they focus on fewer levels than many contemporary models. Due to the low data requirement of these two models, they do not require intense expert knowledge and can be easily applied by users who are not very experienced. In addition, since Fu Model is not limited to industrial accidents, it can be implemented to any area without any modification. Fu Model looks for flaws in safety knowledge, safety awareness, safety habits under unsafe acts. But in HFACS and Swiss Cheese, these are not as distinctive as in Fu Model. Furthermore, Fu Model was able to identify causes outside of the organization that contributed to the accidents because it considered, “external factors” category. However, Fu(2018) has various drawbacks. Fu Model does not make any distinction in unsafe acts, namely it is unclear for illustrated accidents above whether the performed actions are errors or violations. Besides that, the category of “safety culture” is another limitation of Fu Model. “Safety culture” consists of 32 elements (Table 1) and the accurate determination of which one of these elements contribute to accidents is pretty hard because true implementation of this factor depends on experience of safety experts.

Swiss Cheese is a less developed version of HFACS and is not as detailed as HFACS. However, it has its place among the scientific and contemporary models, because it includes the fallible decisions of senior management and safety culture flaws.

Conclusion

In this study Swiss Cheese, Fu (2018) and HFACS models were chosen among the contemporary accident causation models and compared using two case studies reported in literature, a mine explosion accident and an electrical plant accident. This study discussed advantages and possible limitations of these models, and according to this discussion all these models include human and organizational factors and have been found scientific and systematic. However Fu (2018) and HFACS are more modern, since they were developed based on Swiss Cheese. If the models are compared with regards to sectors, HFACS and Swiss Cheese are more suitable for aviation accidents but can be modified to be used for any area. On the other hand, Fu Model is more practical than HFACS, because HFACS requires very detailed data and more extensive experience for implementation. Besides that, HFACS makes essential distinctions for unsafe acts (error vs. violation), which is very significant because an error can be forgivable since it is made by mistake and not on purpose, where a violation cannot be forgiven since it represents violating rules consciously. Nevertheless, Fu Model has an advantage over HFACS, in the sense that it can identify external factors. However, the correct implementation of safety culture category is never easy, because it depends on experiences of the safety analyst. As a result, this study has demonstrated that a new hybrid model can be developed based on Fu(2018) Model and HFACS

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