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Causation of Severe and Fatal Accidents in the Manufacturing Sector

Jesús A. Carrillo-Castrillo

University of Seville, Seville, Spain

Juan C. Rubio-Romero

University of Málaga, Málaga, Spain

Luis Onieva

University of Seville, Seville, Spain

The main purpose of this paper is to identify the most frequent causes of accidents in the manufacturing sector in Andalusia, Spain, to help safety practitioners in the task of prioritizing preventive actions. Official accident investigation reports are analyzed. A causation pattern is identified with the proportion of causes of each of the different possible groups of causes. We found evidence of a differential causation between slight and non-slight accidents. We have also found significant differences in accident causation depending on the mechanism of the accident. These results can be used to prioritize preventive actions to combat the most likely causes of each accident mechanism. We have also done research on the associations of certain latent causes with specific active (immediate) causes. These relationships show how organizational and safety management can contribute to the prevention of active failures.

accident causation accident investigation manufacturing sector preventive actions

1. INTRODUCTION

Directive 89/391/EEC is a substantial milestone in improving health and safety at work [1]. It guarantees minimum health and safety requirements throughout Europe while Member States are allowed to maintain or establish more stringent measures. The Directive introduces the principle of risk assessment as a key element and defines the main elements: hazard identification, worker participation, introduction of adequate measures with the priority of eliminating risk at source, documentation and periodical re-assessment of workplace hazards.

In those tasks, enterprises rely on safety practitioners. Risk assessment and preventive action definition are the main tools that safety practitioners use in their job. There are many tools for risk assessment [2, 3], but, in comparison, very few for preventive action definition. Preventive actions are proposed by safety practitioners based on the existing regulations, but most of the time they have to use good practices as a guide.

When an accident occurs, all preventive and protective measures are audited and, if necessary, reviewed. Although accident (or incident) investigation at company level is a very useful tool for defining preventive actions, most companies do

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Correspondence should be sent to Jesús A. Carrillo-Castrillo, Camino de los Descubrimientos s/n, ETSI, 41006 Seville, Spain. E-mail: jcarrillo@io.us.es.

not have enough accidents to do this and, in any case, this is not what prevention is supposed to be.

Our research focuses on accident investigation performed by public authorities and their potential role in identifying and prioritizing preventive activities. Accident investigation is the main tool used to research the root causes of accidents [4, 5]. From the methodological point of view, accident investigation has to be aligned with accident causation models [6] and to cover different levels of analysis [7, 8].

To draw conclusions from accident investigations, there are two key issues that need to be taken into account. The first one is to analyze accidents that could be reasonably compared and grouped together. This is because most analyses of causes are cross-sectional [9, 10], although some researchers have used a case-control approach [11]. As there is little control of possible confounders, it is important to analyze accidents that are as alike as possible [12, 13].

The second key issue is to code the circumstances and causes so that they can be easily identified. At least in Europe, the harmonized phase III of European Statistics on Accidents at Work (ESAW) offers a uniform and easy classification of circumstances of accidents at work, which permits comparison and proper codification [14]. The ESAW is based on the recommendations of the International Labor Organization [15].

Our research is based on cross-sectional research of accident investigations in the manufacturing sector in Andalusia, Spain. Manufacturing is the sector with the highest number of annual days of absence due to accidents in Europe [16]. The latest incidence rate in the manufacturing sector published by Eurostat is 3097 accidents per 100 000 workers for accidents with over 3 days of absence in the European Union and Norway in 2007.

Andalusia is one of the biggest regions of Europe, it represents ~12% of the Spanish manufacturing sector. The manufacturing sector is defined, like all activities, with codes from 15 to 27 according to Council Regulation 3037/90 [17]. Traffic accidents and accidents of self-employed workers are not included.

Accident causation in the manufacturing sector has been studied from different perspectives. Analyzing self-reported accidents is one of the approaches [18]. Other authors have analyzed accidents investigated in the manufacturing sector, most of them in specific industries [5] and specific types of accidents [19]. Nevertheless, further research is necessary to identify the mechanisms.

Accident causation in manufacturing is an evolving issue. The effects of new technologies and automation [20] and the progressive integration of safety and ergonomics with management systems [21] have changed the types of accident causes in the manufacturing sector.

The main aim of this paper is to analyze the causes of accidents in the most frequent accident mechanisms in production tasks in the manufacturing sector. The results can be used to prioritize the most effective preventive actions.

1.1. Conceptual Framework

The bow-tie model used as a representation of the accident is based on a causation process from hazard to consequences through a central event [22]. In our analysis, we define and classify the possible central events in terms of the codification of two variables included in the ESAW that identify the accident mechanism. Those variables are deviation and mode of injury; they have been used before to identify the accident mechanism [23].

According to the Encyclopaedia of Occupational Health and Safety, the causes of accidents can be classified as active causes such as unsafe acts and unsafe conditions or as contributing causes such as safety management performance, mental condition of worker and physical condition of worker [24]. The latter are also part of latent causes.

Accident investigations should identify both active and latent causes for each barrier breaking in the bow-tie model [5]. As a result of their nature, latent causes are supposed to be contributing causes of active causes [10].

Preventive or protective measures directly aimed at combating the expected causes of an accident mechanism should be considered first. Those expected causes are the most frequently

identified causes. For example, if the accident mechanism of being trapped by a machine is usually related to causes such as not signaling lockout of machines [25], preventive action should be prioritized to eliminate or control that possibility. In the same way that a safety practitioner decides what the most dangerous risks are, a safety manager should implement and enforce the preventive actions related to the most frequent causes of each assessed risk.

Thus, by analyzing the accident causation of each accident mechanism, it is possible to propose the preventive or protective measures that are most likely to be effective.

2. MATERIALS AND METHODS

The accidents included in this study are from the manufacturing sector accident investigations coded and reported in Andalusia.

This paper analyzes accidents within the core of the manufacturing tasks in the manufacturing sector. Most accidents in this sector are included in the 84.0% of accidents occurring on industrial sites (coded with working environment from 010 to 019 in the ESAW [14]) and the 71.4% of accidents occurring during production, manufacturing, processing or storing (coded with working process from 10 to 19 in the ESAW).

Although accidents in the manufacturing sector also occur in other working processes and working environments, those such as service operations, maintenance operations or installation activities are not specifically part of manufacturing activities and should be studied separately.

2.1. Accident Notifications

In Spain, accident notifications are electronically collected in official workplace incident notification forms [26]. All accidents that result in an absence from work of one or more days must be notified. In terms of severity, accidents can be slight, severe or fatal. Medical criteria are applied to classify an accident as slight or severe, depending on the severity of the injuries and the expected period of recovery. Relapses, accidents incurred when traveling to and from work, and others are excluded from the study.

The main variables included in the accident notifications are coded according to the ESAW under headings such as working environment, working process, deviation and mode of contact [14].

Although all accident notifications were available for this research, only data from the accidents that were notified and officially investigated are included.

2.2. Official Accident Investigation Reports

Usually, when an accident is severe or fatal, safety officers from the Andalusian Labor Administration conduct an official accident investigation after the accident notification has been received. Traffic accidents and non-traumatic deaths such as strokes or heart attacks are not usually investigated. Most slight accidents are not investigated, either. From 2004 to 2011, 492 accidents with working environment from 010 to 019 and working process from 10 to 19 in the ESAW [14] were officially investigated. Only 390 of them were non-slight accidents.

In the period analyzed, 22% of severe and fatal accidents were investigated, whereas only 4% of the accidents notified were investigated. Thus, only in severe and fatal accidents were there enough cases to analyze. Despite the low proportion of slight accidents investigated, we tested the hypothesis of differential causation between slight and non-slight accidents as part of this research.

Analysis of the accident causation for the most prevalent accident mechanisms is carried out only for non-slight accidents. This is because few non-slight accidents are investigated and because the differential causation has already been tested. Although non-slight accidents are only 1.4% of the notified accidents [27], efforts should be concentrated on their prevention because of their consequences. Indeed, most accident investigations are of non-slight accidents.

In this research, safety officers investigated all accidents. These investigations are carried out according to internal procedures and an official extended investigation report is submitted. Safety officers take part in training activities on the methodology of investigation, based on the fault

tree method [28]. All data for each accident circumstance are available according to the ESAW methodology [14].

Spain's Instituto Nacional de Seguridad e Higiene (the Occupational Health and Safety Institute) has promoted a national codification system for causes included in official accident investigation reports to facilitate the statistical analysis [29]. In Andalusia, a program devoted to coding officially investigated accidents with the national codification system was introduced in 2004.

The investigated and coded accidents that are included in this research occurred from 2004 to 2011. In the national codification system, there are 255 possible causes [29]. The number of causes per accident investigated varies but in most cases the number of causes is three or four. Codes are defined with four digits, the first identifies the group of causes, the second identifies the subgroup of causes and the other two are the different causes in each subgroup. Digit nine is used for miscellaneous.

The number of causes for each accident is not fixed. Note that all causes can be included in each accident but only one of them can be identified as the main cause, although in some cases no main cause is identified.

According to the levels of analysis, this codification includes causes at four different levels: work and technological system, staff, management and company level. Other levels such as government or regulations are not considered [7].

In terms of accident causation, causes can be active (workspace conditions, protection and service installations, machines, other equipment, and materials and substances) or latent (work organization, safety management and personal factors) [30].

2.3. Methods

Differential causation between slight and non-slight accidents is tested by comparing the proportion of accidents that includes at least one cause in each group or subgroup of causes. Differences in proportion are tested with the large sample simplified method, assuming normal distribution. Confidence intervals that do not include zero identify significant differential causation.

Finally, the analysis of association of accident causation patterns is performed only for non-slight accidents. The association is analyzed with contingency tables. From the preventive point of view, in a statistical analysis of the relationship between two categorical variables, it is better to analyze the relationships at cell level [31].

At cell level, we can identify which categories are associated. This is more useful than the overall relationship of the contingency table of the two variables. Statistical tests at cell level of the associations of each pair of categories are performed using φ and Cramer's *V* coefficients [32].

To get a pattern of the accident causation, the proportions of cases with at least one cause identified in each subgroup of causes are calculated. As an example, if 50% of the accidents analyzed have at least one cause due to personal factors, that proportion is attributed to the subgroup of causes.

The analysis is based on a causation pattern identified by the proportion of cases with at least one cause from each subgroup of causes. In our opinion, it is more important that at least one cause should be identified rather than the number of causes. This is because most of the time the attribution of more than one cause from the same subgroup is redundant. At all events, only 2.3% of the accidents have more than one cause attributed in the same subgroup, so there would be only very slight differences if we had identified the accident causation pattern using the number of causes identified in each subgroup.

We analyzed the contingency table between subgroups of causes and accident mechanisms. The accident mechanisms are identified using the variables Deviation and Contact [23]. We only analyzed the accident mechanisms with a sufficient number of investigated cases. As a rule of thumb, 10 investigated accidents are considered enough for this purpose [33, 34]. Also, we analyzed the contingency table between latent and active subgroups of causes.

SPSS version 18 was used. Statistical results are considered significant with $p < .05$.

3. RESULTS

The proportion of latent causes was 72% in the accident investigation reports analyzed. In 64% of the accident investigations, the main cause was latent (Table 1). In total, 1701 causes were identified in the 492 accident investigations analyzed. In the 390 non-slight accident investigations, 1317 causes were identified.

The subgroups of causes where at least one cause was identified with a high proportion of accidents were Work procedure (42%), Safety activities (38%) and Behavior (30%). The subgroups where one cause was identified as the main cause with a high proportion of accidents were Work method (17%), Behavior (16%) and Design, construction and maintenance (13%).

TABLE 1. Classification of Causes Identified in Accidents Investigation Reports; All Investigated Accidents Are Included, Both Slight and Non-Slight

Kind of Cause	Group of Causes	Subgroup of Causes (Type of Cause)	No. of Cases With Main Cause in Subgroup	No. of Causes Identified in Subgroup	% of Cases Where Causes of Subgroup Are Main Cause
Active	workplace conditions (1)	workplace layout (11)	31	66	47
		housekeeping (12)	11	32	34
	installations, machinery and other equipment (2, 3, 4)	design, construction, maintenance (21, 31, 41)	65	134	49
		protection devices (22, 32, 42)	37	128	29
		signage (23, 33, 43)	2	31	6
	materials and substances (5)	handling and storage (51)	18	45	40
		chemicals (52)	1	9	11
	other	other (13, 19, 49)	4	20	20
Latent	work organization (6)	work method (61)	85	273	31
		activities planning and execution (62)	12	40	30
		training (63)	6	78	8
		equipment selection (64)	16	65	25
	safety management (7)	safety management (71)	18	128	14
		safety activities (72)	36	305	12
	personal factors (8)	behavior (81)	81	200	41
		personal characteristics (82)	5	25	20
		other personal factors (89, 69, 91, 92)	48	122	39
		all groups	476	1701	28
	number of cases with no main cause		16		

The most frequent specific causes are Inadequate work method, Lack of training, Lack of guards, Other individual factors, Failure to use personal protective equipment, Failure to comply with safety rules, Hazards that are not assessed and Non-provision of personal protective equipment (Table 2).

3.1. Differential Causation of Slight and Non-Slight Accidents

Significant differences in the proportion of cases with at least one cause identified in each subgroup have been found (Table 3). Slight accidents are more likely to be caused by problems in Design, maintenance and installation of equipment

TABLE 2. Most Frequent Causes Identified in Investigated Accidents, Both Slight and Non-Slight

		No. of Cases With Cause Identified			No. of Cases Identified as Main Cause		
Code	Description	Slight	Severe	Fatal	Slight	Severe	Fatal
6102	inadequate work method	27	148	10	2	62	3
7206	lack of training	59	69	—	7	7	—
3201	lack of guards	15	61	6	2	25	1
8999	other individual factors	10	67	—	—	1	—
8106	failure to use PPE	32	28	1	8	5	—
8102	failure to comply with safety rules	5	45	4	1	24	2
7201	hazards that are not assessed	9	35	1	—	4	—
7208	non-provision of PPE	18	18	1	6	1	—
4105	access to dangerous parts	7	27	—	4	15	—
…	…	…	…	…	…	…	…
	total number of cases	110	361	21	110	361	21

Notes. PPE = personal protective equipment.

TABLE 3. Differential Causation of Slight and Non-Slight Accidents: Analysis of Proportion of Accidents With at Least One Cause in Each Subgroup of Causes

Subgroup of Causes	Slight (%)	Severe or Fatal (%)	Difference (%)	CI Difference (%)[a]
11 workplace layout	11.6	12.8	1.2	
12 housekeeping	6.3	4.4	–1.9	
13 physical agents	0.9	1.8	0.9	
21, 31, 41 design, maintenance, installation	16.9	2.6	–14.3	[–21.4, –7.2]
22, 32, 42 protective devices	23.2	22.3	–0.9	
23, 33, 43 signage and information	3.6	8.2	4.6	[0.2, 9.0]
51 handling and storage	6.3	5.4	–0.9	
52 chemical substances	0.9	1.8	0.9	
61 work method	29.5	46.2	16.7	[6.9, 26.5]
62 carrying out the tasks	2.7	8.5	5.8	[1.7, 9.9]
63 training and information	5.4	15.9	10.5	[5.0, 16.0]
64 equipment and material selection	7.1	11.8	4.7	
71 safety management	29.5	15.4	–14.1	[–23.3, –4.9]
72 safety activities	53.6	33.6	–20.0	[–30.4, –9.6]
81 behavior	33.9	29.0	–4.9	
82 personal factors	11.6	19.5	7.9	[0.8, 15.0]
91 other	3.6	4.1	0.5	

Notes. CI = confidence interval; a = significant differences (test of differences of proportions assuming normal distribution, $p < .5$). Only CIs that not include 0.0% are included.

and deficiencies in Safety management and Safety activities.

Non-slight accidents are more likely to be caused by deficiencies in Signage and information, inappropriate Work method, errors in Carrying out the tasks, Lack of training and information and Personal factors.

3.2. Mechanisms of Non-Slight Accidents and Causes

We identified the most frequent accident mechanisms among the accidents investigated (Table 4). Significant associations between accident mechanisms and the subgroups of causes were identified with φ coefficient calculation for accident mechanisms with at least 10 cases.

3.3. Latent and Active Cause Relationships in Non-Slight Accidents

The analysis is based on the contingency table between subgroups of active causes and subgroups of latent causes. Each cell is the number of cases with at least one cause in the subgroups of its row and column (Table 5). Significant cell level associations are identified using φ coefficient calculation.

TABLE 4. Differential Causation of the Most Frequent Mechanisms of Non-Slight Accidents; Proportion of Cases With at Least One Cause in Each Subgroup of Causes

	Mechanism (%)									
Subgroup of Causes	**1-1**	**3-4**	**3-6**	**4-4**	**4-5**	**4-6**	**5-3**	**6-3**	**6-5**	**6-6**
11 workplace layout	0	14	21	0	7	14	34**	17	4	8
12 housekeeping	0	14*	5	0	2	2	6	0	0	3
13 physical agents	0	9**	0	5	0	0	0	8	4	0
21, 31, 41 design, maintenance, installation	64***	14	37	43	25	28	13	17	21	47***
22, 32, 42 protective devices	45*	18	21	52	23	23	9*	17	33	29
23, 33, 43 signage and information	9	0	16***	24	7	7	6	8	0	3
51 handling and storage	0	9	11	14*	2	2	13	0	0	3
52 chemical substances	36	0	0	0	0	0	3	0	0	3
61 work method	55	45	42	48	52	40	41	42	50	47
62 carrying out of tasks	18***	14*	5	0	9	9	9	0	4	11
63 training and information	9	14***	21	19	14	14	19	8	17	13
64 equipment and material selection	36	14	11	19	7	12	9	33***	13	8
71 safety management	27	14	16	24	11	14	28***	33	4	21
72 safety activities	36	27	32	57	36	30	28	33	33	34
81 behavior	9	23	21	38	34	44	22	33	38	32
82 personal factors	36	18	5	14	30	16	9	8	21***	24
91 other	0	5	0	0	0	2*	9***	0	0	5
No. of accidents investigated	11	22	18	21	43	43	29	12	24	38

Notes. *$p < .5$ (Cramer's V); **$p < .05$ (Cramer's V); ***$p < .005$ (Cramer's V). Mechanisms are designated with the first digit of the code of deviation and the first digit of the code of mode of injury of ESAW [14]. Deviation codes: 1 = deviation due to electrical problems, explosion, fire; 2 = deviation by overflow, overturn, leak, flow, vaporization, emission; 3 = breakage, bursting, splitting, slipping, fall, collapse of material agent; 4 = loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal; 5 = slipping or stumbling—with fall, falls of persons; 6 = body movement without physical stress (generally leading to an external injury); 7 = body movement under or with physical stress (generally leading to an internal injury); 8 = shock, fright, violence, aggression, threat, presence. Mode of injury codes: 1 = contact with electrical voltage, temperature, hazardous substances; 2 = drowned, buried, enveloped; 3 = horizontal or vertical impact with or against a stationary object; 4 = struck by a moving object, collision; 5 = contact with a sharp, pointed, hard or rough material agent; 6 = trapped, crushed, etc.; 7 = physical or mental stress; 8 = bite, kick, etc. [14].

TABLE 5. Association Between Latent and Active Causes in Non-Slight Accident Investigated; in Each Cell, Number of Cases With at Least One Cause in Both Subgroups of Causes, Latent and Active

Subgroup of Causes	61 Work Method	62 Carrying Out Tasks	63 Training & Info	64 Equipment Selection
11 workplace layout	17*	1	3	4
12 housekeeping	5	1	3	0
13 physical agents	5***	1	4***	2
21, 31, 41 design, maintenance, installation	37	7	16	16***
22, 32, 42 protective devices	37	9	15	10
23, 33, 43 signage and information	14	3*	8*	6
51 handling and storage	5	3	3	1
52 chemical substances	2	1	1	3***

Subgroup of Causes	71 Safety Management	72 Safety Activities	81 Behavior	82 Personal Factors
11 workplace layout	7	21	11	3
12 housekeeping	0	5**	5	1
13 physical agents	0	5	3*	1
21, 31, 41 design, maintenance, installation	14	41***	26	2
22, 32, 42 protective devices	15	36	23	4
23, 33, 43 signage and information	4	14***	6	2
51 handling and storage	4	4*	2	0
52 chemical substances	2	1	0	0

Notes. *$p < .5$ (Cramer's V); **$p < .05$ (Cramer's V); ***$p < .005$ (Cramer's V).

There are associations between accidents caused by Physical agents and causes classified as Work method and Lack of training and information. Deficiencies in Design, maintenance, installation and accidents with Chemical substances are associated with errors in Equipment selection. Deficiencies in Housekeeping, Design, maintenance and installation and Signage and information are associated with errors in Safety activities.

4. DISCUSSION

Our analysis is based on the assumption that accident investigations can be used to identify the most effective preventive activities insofar as there are strong associations between the pattern of causes identified and the accident mechanism.

Unfortunately, we can only analyze the accidents, so we are not able to investigate what successful good practices enterprises without accidents use. Nevertheless, the identification of the most frequent causes of prevention failure is very useful information for those small and medium enterprises without enough accidents [34]. The information this paper provides gives sufficient information on the circumstances of the accidents where the causes were identified for any enterprise with a risk of similar accidents to use to check whether they are implementing appropriate preventive actions.

Thus, accident investigation can fill the gap between risk assessment and preventive action definition. Risk assessment can only provide a ranked list of possible risks but not prioritization of the preventive activities required. Moreover, risk assessment tools safety practitioners use are aimed at technical risks and active causes but not at latent deficiencies in organizations.

If we assume that accidents are a sociotechnical issue, preventive actions need to be aimed at both latent and active possible causes. Moreover, as 71% of the identified causes are latent, there is a need for greater efforts in the areas of organization, safety management and behavior. In our results, we have encountered new evidence of

differential causation between slight and non-slight accidents, an issue already found in earlier research [27, 35, 36]. These results support a separate analysis of severe and fatal accidents.

Differences between slight and non-slight accident causation is very useful information for safety practitioners. According to the accident investigations analyzed, safety management is more effective in controlling slight and repetitive accidents, but if the objective is to prevent non-slight accidents, then organizational issues are more important.

With this result, we analyzed differential causation for the most prevalent mechanism of non-slight accidents. Electrical, explosion and fire non-slight accidents are likely to be caused by deficient Design, maintenance and installation and by errors in Carrying out tasks. Previous research on electrical accidents showed similar results [32]. Specific procedures need to be defined when there is risk of electrical, explosion or fire accidents and, at the same time, correct maintenance of well-designed equipment is essential.

Breakage, bursting, splitting, slipping, fall, collapse of materials non-slight accidents where the worker is Struck by an object are likely to be caused by Lack of training and information, whereas if the contact is Being trapped, the accidents are likely to be caused by inappropriate Signage and information [25]. McGrath recently analyzed the effectiveness of signage in preventing accidents with machinery [37].

Slipping, stumbling or falling non-slight accidents have a different causation depending on the contact. If the contact is with a stationary object, the accidents are likely to be caused by lack of appropriate Safety management and problems with Workplace layout. This association of latent and active failures in these accidents has already been identified as the key for successful preventive action in the case of slips, trips and falls [38].

Non-slight accidents with deviation such as Body movement under or with physical stress when the contact is with Sharp or rough surfaces are likely to be caused by personal factors but if the contact is Horizontal or vertical impact with stationary object, the most likely causes are inappropriate Equipment and material selection. If the contact is Being trapped or crushed, the most likely causes are Inappropriate design, maintenance and installation of equipment as suggested by earlier research [25, 39].

Loss of control non-slight accidents do not show any strong association with any subgroup of causes, possibly due to the heterogeneous nature of this deviation. Intervention to reduce these accidents involves different actions. The absence of a causation pattern for these accidents is unusual and should be considered a potential field for research.

These results show that each mechanism has its own specific pattern of causation in terms of the expected distribution of the type of causes identified. The specific causation pattern of each accident mechanism can be used to identify effective preventive actions, prioritizing those preventive actions aimed at preventing the more frequent causes for each accident mechanism.

At the same time, the results show that combating only the active causes of accidents is not likely to be effective. According to the modern theories of accident causation, the latent causes are contributing factors of the active failures or active causes [5, 29]. Within that conceptual framework, the associations identified in our paper between active and latent causes provide evidence of the mechanism of how safety management and preventive activities contribute to combating active causes [40].

At company level, the analysis can be useful as a way of adding relevant knowledge to the management of occupational safety [41], linking accident scenarios and likely causes of accidents. From an epidemiological point of view, the cross-sectional analysis of the expected causes for each accident mechanism provides a useful initial prioritization of the preventive activities. Finally, from a public administration point of view, these results can be used to make known the most frequent causes of each accident mechanism.

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