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STATISTICAL ANALYSIS OF CONTRIBUTORS TO CHEMICAL PROCESS ACCIDENTS

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A database study of accident contributors in the chemical process industry (CPI) was carried out. All 364 CPI-related accidents available in the Failure Knowledge Database were analysed to identify the main and sub-contributors of the accident. The accident contributors were ranked in accordance to their frequency and importance in accident prevention. The most common accident contributors were the human & organizational aspect in operation (19% of contributors), contamination (11%), flow-related (11%), and heat transfer (10%). In the main contributor analysis, the same classes of contributors were also the most frequent causes of accidents. The four-quadrant analysis identified the most important contributors to be focused on in accident prevention: contamination, flow-related and heat transfer categories. The relationships between the contributors were also studied using an interconnection matrix, which revealed three functional groups of accident contributors. Their relationships were illustrated through an interconnection diagram.

Keywords: accident analysis, accident contributors, contributor interactions.

1.0 Introduction

Analysis of past accident cases is a typical way to study the reasons for accidents and their contributors, which can be used for improving the design and operation of chemical processes. This is sorely needed since in spite of all the efforts the accident rate in the chemical process industry (CPI) has not been decreasing in the USA [1], Asia [2, 3] and Europe [4]. Reasons for this are manifold including the safety management systems used, management knowledge on the process risks, aging industry and cost pressures [5, 6].

It is claimed that the vast majority of accidents (>95%) could have been foreseen and prevented by appropriate application of existing and disseminated knowledge [7]. Almost all accidents have well known causes [8]. To an outsider, it might seem that industrial accidents occurred because nobody knew how to prevent them. In fact, they occurred because we did not use the knowledge available and allowed similar accidents to recur [9]. The weakest link in the experience feedback system is the dissemination and the use of existing knowledge [10, 11]. Therefore more studies should be done on analysing accident cases, publishing lessons learnt and improving the feedback system.

The technical contributors to accidents have been discussed by Nivolianitou et al. [13], who found out that about 70% of the accidents in the petrochemical industry were at least partly caused by equipment failures. Further, Prem et al. [1] analyzed three major accident databases in the USA and found out that 57% - 63% of the accidents were initiated by equipment failures. However, no further analysis was made on the root causes of the equipment failures. A specific analysis on the process equipment failures was recently carried out by Kidam and Hurme [14]. They found that the majority (78%) of equipment failures were caused by technical aspects including faults in design, interface and safety analysis.

The contribution of design and technical aspects to accidents in the CPI has been discussed in the following studies: Drogaris [7] found that the contribution of design to accidents (where the reasons are known) is 70% of accidents, which corresponds to 80% of causes, when the same classification of contributors is used as in our study (see Chapter 2). Sales et al. [12] and Nivolianitou et al. [13] both found that the share of technical and design contributors is about 70% (with our classification). The analysis by Duguid [15] showed that about at least 40% of accidents and about 50-60% of contributors are related to technical and design aspects. However, the classification he used is not easily comparable.

The earlier studies analysed and discussed accident contributors at a very general level. Some of them focused on a specific subject area such as equipment types, design errors, human and organizational faults. Almost all the accident analyses listed the accident contributors based on their frequency. No significant work has been done to rank their importance in accident prevention activities. Further, the interconnection between accident contributors has been ignored and their measures have been based on past experience in qualitative ways.

Therefore, the aim of this paper is to analyze past accident cases in order to clarify which contributors to accidents are the most common, how often they act as main or sub-contributors, how important their roles in accident prevention are, and how they are interlinked to each other. In this paper, the accident contributors are ranked based on their frequency as contributors in general and as main contributors.

2. Research approach

After a series of major accidents in 1970s and 1980s, i.e. Flixborough (1974), Seveso (1976) and Bhopal (1984), reporting systems for abnormal main events were created for the dissemination of accident information. Several accident databases have been created such as the Accident Reporting Information System (IRIS) in the USA, Major Accident Reporting System (MARS) in Europe and Failure Knowledge Database (FKD) in Japan.

Accident Databases are a valuable source of information for loss prevention, but they have also been criticized. Kletz [17] stated that many of the accident reports were incompletely written due to inadequate investigation and competency. Some of them were inaccurately reported due to wrong interpretation of the evidence. Current research shows that the usage of accident reports and databases was less than expected; even safety practitioners did not use accident information regularly [11].

To minimize the problems related to insufficient and inaccurate data as pointed out above, the Failure Knowledge Database (FKD) was selected for this study [18]. This accident database contains old and new accident cases (up to 2004), which are mainly (95%) from Japan. Foreign high impact accidents were also included (e.g. Bhopal, Flixborough, Seveso etc.) The CPI related accidents analyzed here are mainly from the years 1964-2003 (with the median 1990).

The accident reports were carefully reviewed by the nominated committee and contained extensive information on each accident, including a process flow diagram, plant layout and fault tree analysis. The availability of the technical and engineering failure information enables conclusions to be drawn from root causes and lessons from accidents to be created. Hatamura et al. [19] has proposed the structure and case expression used in the FKD database.

For this analysis, all the chemical industry accident cases available on the FKD database were selected, involving 364 cases. The accident reports were analysed to identify the accident contributors and their root causes. The accident contributor classification used is presented in Table 1. The contributors can be grouped into human & organizational (a), technical (b – n) and external factors (o). All the management, organizational and human failures related to plant operation were included in a single contributor called the human and organizational factor (a). Design errors such as poor layout, wrong selection of construction material, etc. are classified under technical factors as well operator error induced by technical factors (i.e. operator-technical interface), as discussed below.

3. Analysis of the accident database

The accident cases were analysed to find both the main and all the contributors to the accidents. Due to the multiple causes of the accidents in the 364 chemical industry cases, 806 accident contributors were recognized, i.e. there were 2.2 contributors per accident on average.

3.1 Frequency analysis of all accident contributors

The distribution of the 806 accident contributors to the 364 chemical industry accident cases analysed is presented in Figure 1. A more detailed presentation of the frequencies and causes of the contributors is given in Appendix 1.

19% of the accident contributors were classified as 'purely' *human and organizational* failures in the plant operation stage. This percentage represents the purely human and organizational error related causes, which were not affected by design or operator-technical interface faults. Similar results were reported by Drogaris [7], who found that 20% of accident causes were operation-related human & organizational faults. Human and organizational failures can be divided further into 1) management level (managerial and safety system) failures and 2) operator level (action based) failures. As shown in Appendix 1, typical contributors in this category are: not following procedures (17%), faults in management of maintenance/repair/cleaning work (13%), human faults in line-up/valve setting (13%), and poor training (12%).

Table 1: The classification of accident contributors

Contributors	Description
Human & organizational faults in operation (a)	Operation related human error and organizational failures. Design and operator-technical interface related human errors are classified as technical contributors.
Contamination* (b)	Trace amounts of unwanted chemicals such as impurities, recycle accumulation, residues, by-product formation, moisture etc.
Flow-related* (c)	Contributors related to fluid flow and transfer such as velocity, viscosity, liquid hammer, reverse flow, leakages etc.
Heat transfer* (d)	Cooling, heating and their effects on physical changes in equipment and process conditions.
Reaction* (e)	Chemical reaction related contributors: unfinished, runaway and unwanted chemical reactions due to chemical reactivity and incompatibilities.
Fabrication, construction and installation* (f)	Faults in design specification, fabrication and installation concerning work planning, quality of work, welding, support arrangements, reconditioning and reusing items.
Layout* (g)	Plant layout, physical arrangement, positioning, equipment accessibility, visual obstacles, signage and colour-coding etc.
Corrosion* (h)	Excessive corrosion attack due to wrong design specification, construction, equipment and piping aging, lack of protection and waterproofing etc.
Construction material* (i)	Inappropriate physical, mechanical and chemical specification of construction material for equipment, piping and components.
Static electricity* (j)	Electric charge generation, accumulation and discharge due to wrong material selection, isolation, lack of earthing and protection when handling process fluids, particulates, dust and powders.
Mechanical failure* (k)	Structural and wall failures due to cracking, fatigue, rotation, moving object/parts, stress, wear and tear etc.
Utilities-related* (l)	Inappropriate design, decision and selection of utility systems and their equipment, availability of utilities as well as back-up system for emergencies.
Vibration* (m)	Vibration resulting from fluids flow, pumping, poor installation, support etc.
Erosion* (n)	Result of fluid movement and flow pattern, gas/liquid phases, particulates, velocity, bubble rupture and internal equipment layout etc.
External factor (o)	Physical and natural events such as bad weather, earthquake, floods, tsunami, lightning, landslides, and some random effects.

*Note: * classified as technical contributors*

79% of the causes were classified as technical, including design, analysis and operator-technical interface errors. In *technical causes*, as shown by Figure 1, the most common accident contributors are associated with process contamination (11%), flow-related faults (11%), heat transfer (10%) and reactions (9%). The causes of these contributors are further elaborated in Appendix A: The most common problem of *process contamination* in the CPI is operator-technical interface related aspects (19%), accumulation of unwanted chemicals (12%), flow-related aspects (11%) and creation of residues (11%). In general, contaminants may be present in the process stream due to accumulation of impurities, formation of by-products, insufficient purging/cleaning of process residues, products of corrosion and erosion, and equipment / pipeline sharing. Process contamination may also occur as a result of introducing an unintended chemical, which is categorized under flow-related contributors.

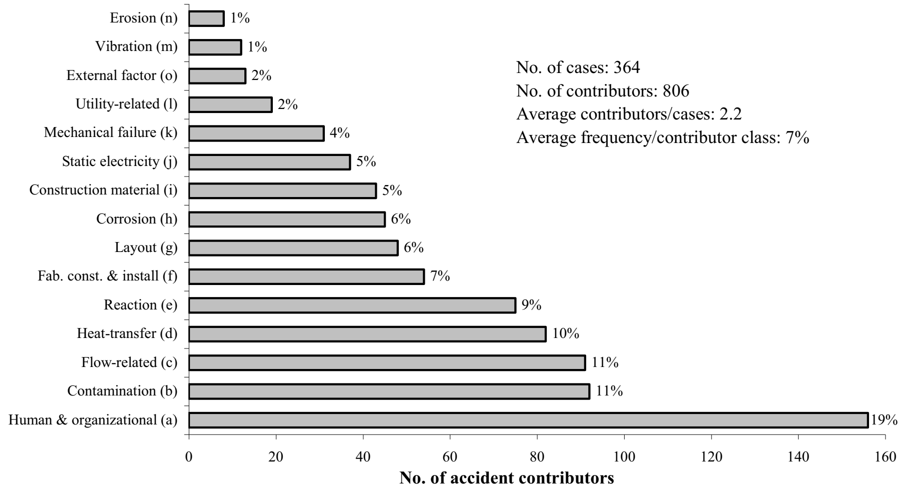

Figure 1: The distribution of accident contributors (% of all contributors)

Flow-related accidents were most often related to faults in operator-technical interface (33%), fluid movement (14%) and poor structural/layout implementation (12%). These factors led to incorrect chemical transfer, overflow, the siphon effect or valve handling, which resulted in chemical release, unintended chemicals mix-up, unwanted reaction, fire or explosion.

10% of process accident contributors were linked with faults in *heat transfer* activities. Typical issues are unexpected heat generation due to excessive heating and insufficient heat removal (16%), operator-technical interface related aspect (12%), thermal expansion phenomena (10%), and local heating or creation of hot spots (9%).

Reactions contributed to about 9% of accident causes in the CPI. Most of the unintended chemical and runaway reactions are due to lack of analysis during chemical process development and design, which generate incorrect data for design. Among critical underlying factors are unwanted reactions that generate hazardous chemicals (21%), an unwanted reaction with incompatible heat transfer medium (15%), no or poor mixing (12%), supply of too much reactant or catalyst (11%), and operator-technical interface related aspects (11%).

Accident contributors such as poor *fabrication/construction/installation* (7%) were also significant. In general, the integrity of the process equipment and its piping system is very much dependent on the quality of its fabrication, construction and installation. Typical issues are linked to bolt tightening (22%), poor work quality (22%) and less than adequate supports (13%).

Poor *layout* (6%*)* increases the risk of accidents due to inappropriate physical arrangement (36%), dead-end issues (27%) and operator-technical interface related aspects (13%). Incorrect physical arrangement will increase plant damage due to the domino effect.

Corrosion (6%) is a common problem in the CPI, the most common cause being obviously an unsuitable construction material (24%). Aging (13%), stress concentrated effects (13%) and abnormal temperature (11%) come next.

Material of construction (5%), *static electricity* (5%) and *mechanical failure* (4%) accident contributors are related to design errors such as inappropriate selection of construction material and inadequate design specifications. These accident contributors seem to be strongly interconnected (discussed later in Section 3.5). The complete accident contributor ranking for chemical processes is presented in Appendix 1.

3.2. Operator-technical interface induced causes

In this paper, operator-technical interface faults were also included as technical causes. The operator-technical interface errors are not strictly design errors, but they can cause operators to make a mistake that leads to an accident. Typical examples of these technical interface induced human failures include problems caused by wrong equipment or component labelling or positioning, confusing control panel display, and poor visibility or accessibility.

Based on the data presented in Appendix 1, the share in interface-induced contributors is about 11% in total. The significance of operator-technical interface induced accident causes varies greatly depending on the contributor, as shown by Table 2. The most critical category is the flow-related accident contributors based on both the share and frequency: 33% of flow-related accident contributors are related to faults in the operator-technical interface. This corresponds to 1/3 of the interface-induced causes. The other frequent interface-affected contributors are contamination and heat transfer. These three make up 2/3 of all interface-related causes. Utility-related contributors were also greatly affected by interface problems (26%) but their frequency is small.

The large share in flow- and utility-related contributors is understandable, since the piping systems make a complicated network with many connections and valves. Unfriendly routing and labelling create a confusing and unsafe user interface, which leads to wrong line-ups and accidents.

Table 2: Share of operator-technical interface faults in each accident contributor

Accident contributor	Frequency of the contributor	Share of interface faults	Number of interface faults
Flow-related (c)	91	33%	30
Contamination (b)	92	19%	17
Heat transfer (d)	82	12%	10
Reaction (e)	75	11%	8
Layout (g)	48	13%	6
Static electricity (j)	37	17%	6
Utilities-related (l)	19	26%	5
Fab, const & install (f)	54	8%	4
Mechanical failure (k)	31	3%	1
Total			*87 806= 11%*

3.3 Main contributors of accidents

In general, accidents occur due to multiple causes. An analysis of the main and sub-contributors of accidents was done and their interdependency analysed. First, the main contributing factor was identified for the 364 accident cases. The main contributor was considered to be the main factor that immediately initiated or triggered the accident. In some cases, the main contributor can initiate or trigger the accident alone. The sub-contributors also make a significant contribution to the accident, however their roles are less important and are considered as supporting factors only. If the main contributor were removed, the accident would not happen at all or would occur with a much lower probability. Table 3 presents the frequencies of all contributors and the main contributors.

As seen from Table 3, the main contributors to accidents are 83% technical, 16% human & organizational and 1% external when the design & analysis errors and operator-technical interface faults are counted as technical contributors. The share of technical contributors (83%) is slightly higher in the main contributors than in all contributors (79%).

The most common main contributors to accidents are human and organizational aspects (16%), followed by process contamination (14%), flow-related aspects (13%), heat transfer (12%), layout (10%) and fabrication/construction/ installation (10%). The ranking list of the four most frequent contributors is the same for main contributors and all contributors.

Table 3: Frequencies and share as main contributors of accidents

Contributing Factors	Frequency				Share as main contributor (SMC)
	As contributor		As main contributor		
Layout (g)	48	6%	38	10%	79%
Construction material (i)	43	5%	29	8%	67%
Fab. Const. & installation (f)	54	7%	35	10%	65%
Corrosion (h)	45	6%	25	7%	56%
Contamination (b)	92	11%	50	14%	54%
Flow-related (c)	91	11%	48	13%	53%
Heat transfer (d)	82	10%	43	12%	52%
Reaction (e)	75	9%	29	8%	39%
Human & organizational (a)	156	19%	60	16%	38%
External factor (o)	13	2%	3	1%	23%
Utilities-related (l)	19	2%	3	1%	16%
Static electricity (j)	37	5%	1	0.3%	3%
Mechanical failure (k)	31	4%	-	-	-
Vibration (m)	12	1%	-	-	-
Erosion (n)	8	1%	-	-	-
TOTAL / average:	806	100% (7%)	364	100%	100% (45%)

Some contributors such as mechanical, vibration and erosion do not appear at all as main contributors. Therefore many other contributors appear more frequently as main contributors than as contributors in general. There is a reason for this. The main contributor is the one that initiates the accident. For instance, in a piping loss of containment accident, the mechanical failure is considered as the end result of the accident whereas the main contributor is e.g. corrosion, layout or the construction material.

3.4 Importance analysis of accident contributors

In this section an importance analysis of accident contributors is carried out, which is based on their share as main contributors (SMC) and on four-quadrant analysis. The analysis creates an importance ranking of accident contributors. The result can be used as guidance for safer design and operations in the CPI by focusing hazard identification activities on the most risk-prone aspects of the process.

In general, the frequency as main contributor is an indicator of the importance of the contributor in accident prevention. The SMC of an accident contributor means how often it is a main contributor compared to its presence in general as an accident contributor. Therefore the SMC shows the potential of an accident contributor to be the main contributor to an accident. For example, layout is present as a contributor 48 times and as a main contributor 38 times, thus its SMC is 38/48 = 79% (Table 3). Even though the SMC does not tell us anything about the probability of accidents, a high SMC is an indicator of the contributor's potential to cause an accident alone, not only contributing as a sub factor.

The SMC of the accident contributors are shown in Table 3. The table shows that there are large differences in the SMCs of accident contributors. The highest SMCs are for layout (79%), unsuitable construction material (67%) and errors in fabrication, construction and installation (65%). The average value of the SMCs is 45%, which can be used as a benchmark for comparison. Below, the SMC and frequency data of accident contributors are utilized to carry out a risk importance estimation of the accident contributors.

Figure 2 presents the SMC versus the frequency of occurrence of accident contributors based on data from Table 3. A four-quadrant analysis is carried out in order to rank the importance of accident contributors in accident prevention. The figure is divided into four quadrants according to the average SMC values and frequency of occurrence. As seen from Figure 2, the accident contributors can be grouped into three clusters, based on their similar positioning in terms of frequency and SMC. Reaction (e) and human & organizational (a) contributors do not fit in any of the clusters. The clusters are summarized in Table 4.

The most frequent cluster consists of heat transfer (d), contamination (b) and flow-related (c) contributors. These three are also the most frequent main contributors after human & organizational (a) causes and correspond to 39% of main contributor frequency (Table 4). Common to these contributors is the large share of operator-technical interface related faults (see Table 2). This cluster is most capable of causing accidents due to its high frequency of occurrence and SMC. Therefore, these accident contributors should be focused on in accident prevention activities.

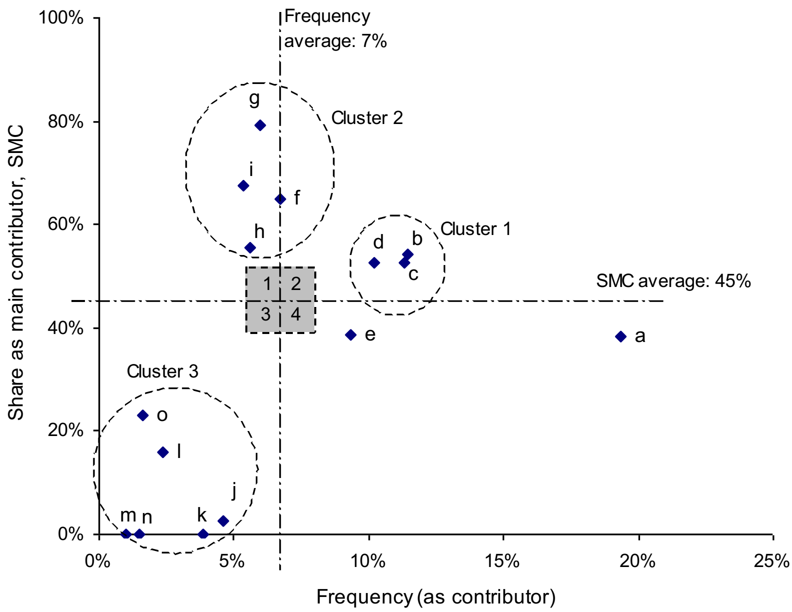

Figure 2: Share as main contributor (SMC) vs. frequency as accident contributors (for the notation see Table 1)

Table 4: Clusters of main contributors and frequency as main contributor.

Cluster 1	%	Cluster 2	%	Cluster 3	%	Outside clusters	%
Contamination (b)	14	Layout (g)	10	Utility-related (l)	0.8	Hum & org. (a)	16
Flow-related (c)	13	Fab./const/inst (f)	10	External factor (o)	0.8	Reaction (e)	8
Heat transfer (d)	12	Const. material (i)	8	Static electricity (j)	0.2		
		Corrosion (h)	7				
Total	39	Total	35	Total	2	Total	24

The second cluster consists of faults in layout (g), construction material (i), fabrication-construction-installation (f) and corrosion (h). This cluster is higher in SMC but less frequent compared to cluster 1 (Table 3). These contributors correspond to a total of 35% of the main contributor frequency (Table 4). Common to these faults is their engineering character, associated mostly with materials, resistance, mechanical aspects, manufacturing, installation, shape and layout. Layout faults are the highest in the SMC accident contributor list. Layout, however, comes fifth in the main contributor frequency (Table 3). This cluster is second in main contributor frequency and also deserves attention in accident prevention.

The third cluster is made up of less common and less severe contributors. They correspond to only 2% of main contributors. Outside the clusters are human & organizational contributors (a) in plant operation, which is the most common main contributor with a 16% share and reaction faults (e) with an 8% share. They both have somewhat unique characteristics. The first is not technical but purely human- and organization-related. It should be focused on in plant operation. The reaction contributor is more chemistry-related but has connections to other contributors as seen in the next section.

Since a contributor with a high SMC has a higher capability of causing accidents as such, not only contributing as a sub-factor, accident prevention should focus on the high SMC contributors which have a high frequency (i.e. cluster 1). Therefore, the importance ranking of the most potential contributors to accidents are cluster 1: process contamination, flow-related & heat transfer, followed by cluster 2: layout, fabrication/construction/installation, construction material & corrosion, and those outside the clusters: human & organizational and reaction due to their high occurrence frequency and SMCs.

3.5 Interconnection of accident contributors

Some accident contributors have a strong relation to one another. Therefore, a correlation study between accident contributors was carried out using an interconnection matrix of main contributors and their sub-contributors, as presented in Table 5. The main contributing factors are shown in the leftmost column and the number of sub-contributors in the rightmost columns. For example, contamination is a main contributor 50 times and the human & organizational aspects are its sub-contributor 15 times, reactions 18 times etc. A high number of combinations represent a strong connection between the accident contributors. Through this study, the unique interconnection characteristics for the main contributors can be found quantitatively. The most significant ones are shown in bold.

As seen from Table 5, the human & organizational sub-contributor is important for all cluster 1 contributors (contamination, flow and heat transfer) and for half of cluster 2 (layout and construction material). However, the rest of the cluster 2 contributors (fabrication/construction/installation and corrosion) have mechanical aspects as the leading sub-contributor. As the main contributor, human and organizational faults have a strong connection with flow-related, heat transfer and static electricity faults.

Figure 3 illustrates the complicated interconnections of accident contributors semi-quantitatively. A thick line represents the strongest correlation between two accident contributors, while a thin line shows a strong correlation and a dotted line a medium correlation.

It can be seen from Figure 3 that flow-related and heat transfer contributors have the strongest two-way correlation with human and organizational factors. Layout and construction material have the strongest one-way connection with human and organizational factors. Contamination and heat transfer are strongly linked to reaction. The mechanical contributors such as mechanical failure, corrosion and fabrication/ construction/ installation have strong interconnections. In conclusion, from Figure 3, three functional groups of accident contributors can be identified, which partly overlap:

Table 5: Number of interconnections between main and sub-contributors of accidents.

Main contributors	Cluster	No. as main contributor	Sub-contributors														
			Human/organizational	Contamination	Flow-related	Heat transfer	Layout	Fab. const. & inst.	Reaction	Const. material	Corrosion	Utilities	External factor	Static electricity	Mechanical	Vibration	Erosion
Human/organizational (a)		60		7	**12**	**11**	1	1	5	0	0	2	1	**10**	2	0	0
Contamination (b)	1	50	**15**		4	2	3	0	**18**	2	3	1	1	6	3	1	0
Flow-related (c)	1	48	**19**	**11**		4	2	1	5	1	2	1	1	2	3	0	1
Heat transfer (d)	1	43	**16**	4	2		0	6	**10**	1	0	5	0	4	0	0	0
Layout (g)	2	38	**17**	**9**	**8**	2		1	3	1	3	0	0	3	1	1	2
Fab. const. & inst. (f)	2	35	5	0	2	**6**	2		1	3	2	1	2	2	**9**	5	1
Reaction (e)		29	**9**	2	4	**10**	0	1		0	1	4	0	0	0	0	0
Const. material (i)	2	29	**10**	1	**9**	1	1	6	2		**8**	0	1	**8**	1	1	1
Corrosion (h)	2	25	4	**8**	2	2	1	2	1	6		1	4	0	**12**	1	3
Utilities (l)	3	3	0	0	0	1	0	1	1	0	1		0	1	0	0	0
External factor (o)	3	3	0	0	0	0	0	0	0	0	0	1		0	0	3	0
Static electricity (j)	3	1	1	0	0	0	0	0	0	0	0	0	0		0	0	0
All contributors		364	156	92	91	82	48	54	75	43	45	19	13	37	31	12	8
Sub-contributors			96	42	43	39	10	19	46	14	20	16	10	36	31	12	8

- *Human and organizational* failures are especially related to flow-oriented problems (such as transfer and handling of chemicals), heat transfer activities, layout issues, static electricity control and construction materials. Implementing a good safety management system could prevent many such accidents.

- The second group observed is *reaction, heat transfer*, *contamination*-oriented. Process contamination is created by or causes unwanted chemical reactions, which could be prevented by identifying possible routes and sources of contaminants (i.e. layout and flow-related factors) and by reducing operating errors (i.e. the human aspects). Heat transfer and reaction are very closely related and their effects on process safety should be considered jointly.

- Third is the group of *mechanic*al & *material* contributors. Mechanical faults are affected by fabrication/construction/installation and by corrosion, which is affected by construction materials.

In general, the interconnection study shows that in many cases, accident contributors cannot be treated as single entities in accident prevention. An overall safety approach is needed which includes both technical and human & organizational factors.

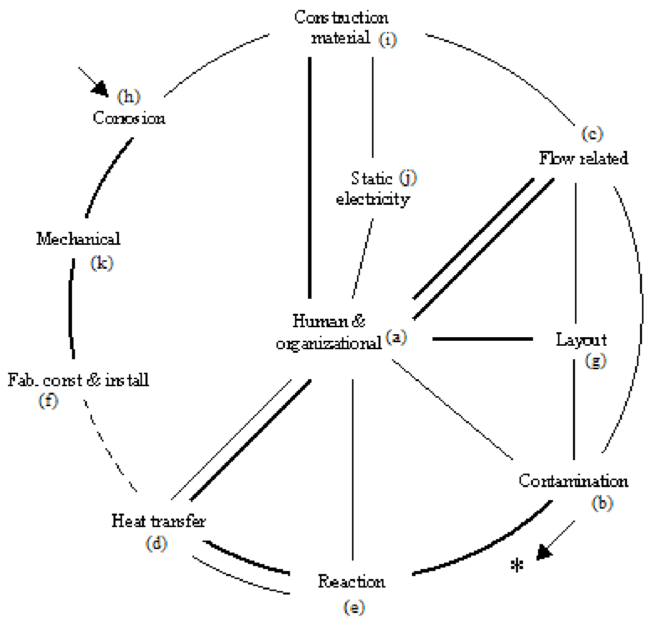

Figure 3: Interconnection diagram of accident contributors (the thicker the line, the stronger the interconnection)

4.0 Discussion and Conclusion

A study was carried out of all 364 chemical process industry accident cases available in the FKD database. In this paper, 15 accident contributors were studied in detail in order to identify the causes of accidents. Their importance in accident prevention and their interconnection were investigated as main and sub-contributors. Frequency analysis appeared to be a useful tool in extracting information from past accidents.

It was found that nearly all accidents have several types of causes. The majority of contributors to accidents were technical (79%), followed by 'purely' human and organizational causes in operation (19%), and external (2%) causes. The result corresponds quite well the average of results (73%) published earlier [7, 12, 13] when the same classification is used. However Drogaris [7] found nearly the same share of technical contributors 81%.
A new finding is the share of the operator-technical interface (11%) as an accident contributor, which has previously been unclear in the CPI. Operator-technical interface errors refer to accident contributors resulting from design and other technical functions, which were not technically faulty but caused operators to make mistakes that led to accidents. For example, flow-related accidents include a large number of operator-technical interface caused faults, since the physical arrangement and labelling of piping systems is sometimes confusing.

The most common accident contributors were human & organizational related causes in operation 19%, contamination 11%, flow 11% and heat transfer 10% related causes. There are always multiple contributors in accidents, 2.2 on average. The ranking list of the four most common main contributors is the same as above for all contributors but the frequencies differ somewhat (16, 14, 13 and 12%, respectively). It was also found that some accident contributors act relatively more often as main than sub-contributors. The measure used for this is called SMC (i.e. the frequency of the contributor when acting as the main contributor divided by the frequency as a contributor in general). For instance, the SMC of layout is 79%. A contributor with a high SMC has a higher capability of causing accidents as such without sub-contributors.

Using a four-quadrant analysis of SMC versus occurrence frequency, it was possible to find clusters of accident contributors with similarities in character. In accident prevention, hazard identification should be focused on the high SMC contributors (i.e. those which act most often as main contributors) that also have a high frequency. In chemical plant design, the focus should therefore be foremost on the first cluster identified (i.e. contamination, flow and heat transfer faults). The first cluster corresponds to 39% of accident main contributors and 66% of the operator-technical interface induced accident contributors. Therefore, if the aim is to reduce frequent but not well-known operator-technical interface induced accidents, the focus should be on the first cluster. As the next priority, attention should be given to the second cluster with layout, mechanical and material aspects. This cluster has a high SMC but the contributors are less frequent.

It was also possible to determine the unique characteristics of how contributors combine with each other. This interconnection analysis revealed three functional groups of accident contributors:

- Human and organizational related group – flow, heat transfer and layout oriented contributors have a strong interconnection to human & organizational contributors.
- Reaction contributors have a strong connection to heat transfer and contamination, which is quite understandable from a reaction hazard point of view.
- The third group is mechanical, fabrication-construction-installation, corrosion, and construction material related contributors.

In conclusion, the paper reports the discovery and ranking of the most common accident contributors and their potential to cause accidents by analysing past accident cases. The result gives the priority to be followed in order to prevent accidents effectively in the design and safe operation of chemical processing plants.

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Appendix 1: The frequency and causes of accident contributors in the CPI

1. HUMAN & ORGANIZATIONAL, 156 out of 806 (19%)

1.1. Not following procedure, 17%
1.2. Maint./repair/cleaning, 13%
1.3. Line-up/valve setting, 13%
1.4. Poor training, 12%
1.5. Poor safety mgt system, 8%
1.6. Contractor mgt, 6%
1.7. Management of change, 6%
1.8. Poor communication, 6%
1.9. Poor planning, 6%
1.10. Hot work, 4%
1.11. Wrong instruction, 4%
1.12. Poor ventilation, 3%
1.13. No operating procedure, 1%
1.14. Confined space entry, 1%

2. CONTAMINATION, 92 out of 806 (11%)

2.1. Operator-technical interface, 19%
2.2. Accumulation, 12%
2.3. Flow, 11%
2.4. Residue, 11%
2.5. Side reaction-hazard comp, 9%
2.6. Cleaning, 7%
2.7. Concentrated, 7%
2.8. Valve leaking, 7%
2.9. Wall failure, 5%
2.10. Waste, 5%
2.11. Structural/layout, 4%
2.12. Management of change, 3%

3. FLOW-RELATED, 91 out of 806 (11%)

3.1. Operator-technical interface, 33%
3.2. Fluid movement, 14%
3.3. Structural/layout, 12%
3.4. Valve leaking, 9%
3.5. Reverse flow, 9%
3.6. Blockage, 8%
3.7. Pressure diff/vacuum, 8%
3.8. Management of change, 3%
3.9. Trap/closed condition, 2%
3.10. Controller malfunction, 2%

4. HEAT TRANSFER, 82 out of 806 (10%)

4.1. Heat generation, 16%
4.2. Operator- technical interface, 12%
4.3. Thermal expansion, 10%
4.4. Hot spot, 9%
4.5. Valve leaking, 7%
4.6. Flow, 7%
4.7. No cooling, 6%
4.8. Hot bolting, 6%
4.9. Insufficient capacity, 6%
4.10. Concentrated/dried, 5%
4.11. Mechanical failure, 5%
4.12. Insufficient detection, 4%
4.13. No mixing, 2%
4.14. Structural/layout/positioning, 2%
4.15. Control malfunction, 1%
4.16. Management of change, 1%

5. REACTION, 75 out of 806 (9%)

5.1. Unwanted reaction- hazardous comp. 21%
5.2. Unwanted reaction- HTM, 15%
5.3. No or poor mixing, 12%
5.4. More reactant/catalyst, 11%
5.5. Operator- technical interface, 11%
5.6. Heat accumulated-react, 7%
5.7. Process deviation-TPC, 8%
5.8. Unfinished reaction, 4%
5.9. Accumulate-react, 3%
5.10. No cooling, 3%
5.11. Higher solvent recovery rate, 3%
5.12. Dried condition/hot spot, 3%
5.13. Dissolved and diffused, 1%

Note:
HTM – heat transfer medium,
TPC – temperature, pressure and concentration.

6. FAB., CONST. & INSTALLATION, 54 out of 806 (7%)

6.1. Bolts tightening, 22%
6.2. Poor work quality, 22%
6.3. Support, 13%
6.4. Stress concentrated, 9%
6.5. Welding, 9%
6.6. Work planning, 9%
6.7. Gasket-reused, 7%
6.8. Operator- technical interface, 7%

7. LAYOUT, 48 out of 806 (6%)

7.1. Physical arrangement, 36%
7.2. Dead-end, 27%
7.3. Operator- technical interface, 13%
7.4. Positive isolation, 8%
7.5. Flow restriction, 8%
7.6. Sizing & shape error, 4%
7.7. Support error, 4%

8. CORROSION, 45 out of 806 (6%)

8.1. Unsuitable material, 24%
8.2. Stress concentrated, 13%
8.3. Aging deterioration, 13%
8.4. Abnormal temperature, 11%
8.5. Welding defect, 7%
8.6. Turbulent flow, 7%
8.7. Inadequate waterproofing, 7%
8.8. No flow, 7%
8.9. Management of change, 4%
8.10. Inlet shape, 4%
8.11. Normal thickness spec, 2%

9. CONSTRUCTION MATERIAL, 43 out of 806 (5%)

9.1. Unsuitable component/part, 33%
9.2. Chemical resistance spec, 28%
9.3. Mechanical spec, 21%
9.4. Material miss-match, 14%
9.5. Shape, 5%

10. STATIC ELECTRICITY, 37 out of 806 (5%)

10.1. Charge isolation, 32%
10.2. Non-conductor material, 27%
10.3. Operator- technical interface, 17%
10.4. Fine powder, 8%
10.5. Flow-liquid, 8%
10.6. Moving object, 5%
10.7. Spray /mist, 3%

11. MECHANICAL FAILURE, 31 out of 806 (4%)

11.1. Crack - cyclic load, 42%
11.2. Weld line-crack, 19%
11.3. Fatigue -high-cycle, 10%
11.4. Vibration, 10%
11.5. Stress corrosion cracking, 6%
11.6. Wear n tear, 6%
11.7. Gap-creep phenomenon, 3%
11.8. Operator- technical interface, 3%

12. UTILITY, 19 out of 806 (2%)

12.1. Operator- technical interface, 26%
12.2. Agitator - fail, 16%
12.3. Power failure, 11%
12.4. Valve leaking, 11%
12.5. Cleaning agent-flammable, 5%
12.6. Detection fail, 5%
12.7. Incompatibility, 5%
12.8. N2 blanket, 5%
12.9. Control system, 5%
12.10. Utility not available, 5%
12.11. Vacuum fail, 5%

13. EXTERNAL FACTORS, 13 out of 806 (2%)

13.1. Earthquake-sloshing, 46%
13.2. Sea water, 23%
13.3. Lightning, 15%
13.4. Freezing, 8%
13.5. Heavy rain, 8%

14. VIBRATION, 12 out of 806 (1%)

14.1. Flow movement, 25%
14.2. Inadequate support, 25%
14.3. Pump operation, 17%
14.4. Aging degradation, 8%
14.5. Cyclic stress, 8%
14.6. Initial defects, 8%
14.7. Poor installation - screw, 8%

15. EROSION, 8 out of 806 (1%)

15.1. Turbulent, 38%
15.2. Two-phase flow, 13%
15.3. High velocity, 13%
15.4. Inlet shape, 13%
15.5. Mist condition, 13%
15.6. Solid particles, 13%