SAFETY SCIENCE Monitor
Issue 1 2010
Article 3
VOL 14

WHICH MANAGEMENT SYSTEM FAILURES ARE RESPONSIBLE FOR OCCUPATIONAL ACCIDENTS?

LINDA J. BELLAMY
White Queen Safety Strategies, NL. Communications to: Dr Linda J Bellamy, White Queen BV, PO Box 712, 2130 AS Hoofddorp, The Netherlands. Email: linda.bellamy@whitequeen.nl

MARTIJN MUD
RPS Advies, NL

MARTIN DAMEN
RIGO, NL

HANS BAKSTEEN
Rondas, NL

OLGA ANEZIRIS
NCSR Demokritos

IOANNIS PAPAZOGLOU
NCSR Demokritos

ANDREW R. HALE
TU Delft, NL

JOY I. H. OH
Ministry of Social Affairs and Employment, NL

ABSTRACT

In The Netherlands an extensive program of work by the Ministry of Social Affairs and Employment began in 2003 to improve worker safety. Within this program the Workgroup Occupational Risk Model - WORM - developed a model for quantifying work activity risks. This model was further developed and turned into a working software tool for performing an occupational risk assessment in 2008. The numerator data for the model were extracted from results of the detailed analysis of 9139 inspector investigations of reportable accidents. The analysis used the software Storybuilder for capturing the richness of the data in a graphical bowtie structure. 36 hazard type structures were built resulting in the identification of 400 safety barriers. Of identified barrier failures there were around 16,000 known organisational failure events across 8 management delivery systems: motivation, procedures, communications, ergonomics, competence, availability, equipment, conflict resolution. This paper concerns the first comprehensive analysis of these delivery systems failures. The results of the analysis showed differences in the dominant organisational failure types according to hazard type. For example, failure to adequately deliver plans and procedures to barrier related tasks is the most frequent management cause for loss of containment accidents but is much less dominant in fall from ladders or stairs where motivation and attention play a bigger role. This suggests that organisations require emphasis on different management delivery systems for the safety barriers depending on the hazard.

1. INTRODUCTION AND BACKGROUND

1.1 Introduction

From 2003 the Ministry of Social Affairs and Employment (SZW) has supported the development of an occupational risk model with the purpose of providing employers with a choice of measure aimed at reducing the risk to employees of suffering injury or death as a result of job-related incidents. The modelling work and supporting software programs were completed in 2008 and this is described in a detailed report (RIVM 2008). As part of the development a comprehensive set of scenarios to cover the full range of occupational accidents was made based on a detailed analysis of around 9,000 occupational accident investigations made by the Dutch Labour Inspectorate. Thirty-six models were built each addressing a particular hazard, like "struck by moving vehicle". From the accident models logical bowties were built and subsequently surveys carried out to derive exposures of the Dutch population to the hazards. This paper addresses only the accident analysis.

The analysed accident database has a big potential to answer questions about accident causation, and this potential is currently being used by the Dutch Labour Inspectorate to provide input to inspections in specific industry sectors such as construction (Ale et al 2008), for specific issues such as accidents to young workers and for specific activities such as operating a forklift truck. The analyses carried out for this paper were part of a project undertaken together with TU Delft to further exploit the goldmine of information in the dataset.

1.2 The aim of the paper

The main aim of this paper is to demonstrate the lessons learned about occupational safety management from a detailed analysis of the underlying causes of serious reportable occupational accidents. These accidents occurred in The Netherlands in the period 1998 to February 2004. The paper gives some general illustrative results in order to show the nature of the data. It then particularly concentrates on the management system failures which underlie the absence or failures of safety barriers and makes a comparison among the types of management failure across different types of occupational accident hazard. The reason for emphasising in this paper the organisational aspects of safety barrier failures is that it appeared from the accident analysis that different types of hazard required different emphasis in terms of management of the safety barriers. This has important implications when considering specific workplaces and their specific hazards in tailoring the safety management system. For example, following the BP Texas refinery accident in the US in 2005, there has been severe criticism of the use of occupational lost time injury data as a performance indicator for the safety management of chemical major hazards:

"The safety measures focused primarily on occupational safety measures, such as recordable and lost time injuries. This focus on personal safety had led to the sense that safety was improving at the site. There was no clear focus or visibility on measures around process safety, such as lagging indicators on loss of containment, hydrocarbon fires, and process upsets." Baker (2007) p.223

The BP Texas accident was a loss of containment (LOC) accident. The Dutch occupational accident data included a LOC of chemicals category which, although not necessarily from major hazard sites, could nonetheless be compared to other occupational hazard categories like being struck by a moving vehicle, contacting electricity, or falling from a scaffold. It was therefore considered a valuable exercise to make comparisons of underlying organisational factors amongst these hazards since the data have hitherto never been available.

In this paper the nature of the accident data and the method of analysis are described in order to provide the full context of the analysis. In presenting the results produced for this paper, these concentrate on the management delivery systems and the different failure patterns observed for the different hazards.

1.3. Background to the accident analysis

The extent and nature of the accident analyses and the subsequent risk model development has no known precedent. In 2003 the possibility of capturing detailed patterns of underlying causes through to a complete risk quantification was considered extremely challenging by the former Director General of the UK's Health and Safety Executive and the former Director of Science and Technology in a study commissioned by the Dutch Ministry of Social Affairs and Employment (Rimington et al, 2003). This challenge was nonetheless taken up.

In the early stages of the project an analysis of thirty-six occupational hazard types had been defined based on an existing model developed by the Dutch Labour Inspectorate of the Ministry of Social Affairs and

Employment (SZW). Eight types of management delivery systems for the tasks of providing, using, maintaining and monitoring of safety barriers were modelled (RIVM 2008) based on an earlier research model I-RISK for risk based auditing of a safety management system (Bellamy et al 1999, Guldenmund et al 1999). The modelling approach used in the current project, in the context of how it has influenced and been influenced by other projects for prioritisating prevention, has been discussed by Hale et (2007). In the current project the safety barrier concept, derived from Haddon (1973) and the hazard-barrier-target model (Schupp et al 2004) was further developed by showing failures in a causal chain of events (scenarios) beginning with an activity and leading to injury or death. The concept of a chain of events being reproduced in the form of a story was also an early decision in the modelling work, inspired by Murray and Dolomount (1995) who used narratives of fisherman to help understand and prevent accidents. Our own approach was to maintain as much detail as possible of each accident “story” by reproduction as a structured series of events (a scenario) in the software Storybuilder™ (www.storybuilder.eu).

Although a lot about accident causes for specific hazards is already known, such as the information that can be found on the European Agency for Safety and Health website (OSHA 2009), there is far less known about the statistics of the underlying management aspects.

2. ACCIDENT DESCRIPTIONS

2.1 Database of the Dutch Labour Inspectorate

In 2004-2006 a team was formed for analysing occupational accident investigation reports made available by the Dutch Labour Inspectorate. In this period the software tool StoryBuilder was evolved to support the development of an events structure (Bellamy et al 2006, 2007 & 2008). Accidents were analysed in order to build cause and effect event structures according to strict building rules. The key components of these structures are safety barriers and their modes of failure which were identified from the accident investigations by applying a set of building rules. An example of an accident in StoryBuilder is shown in Figure 1.

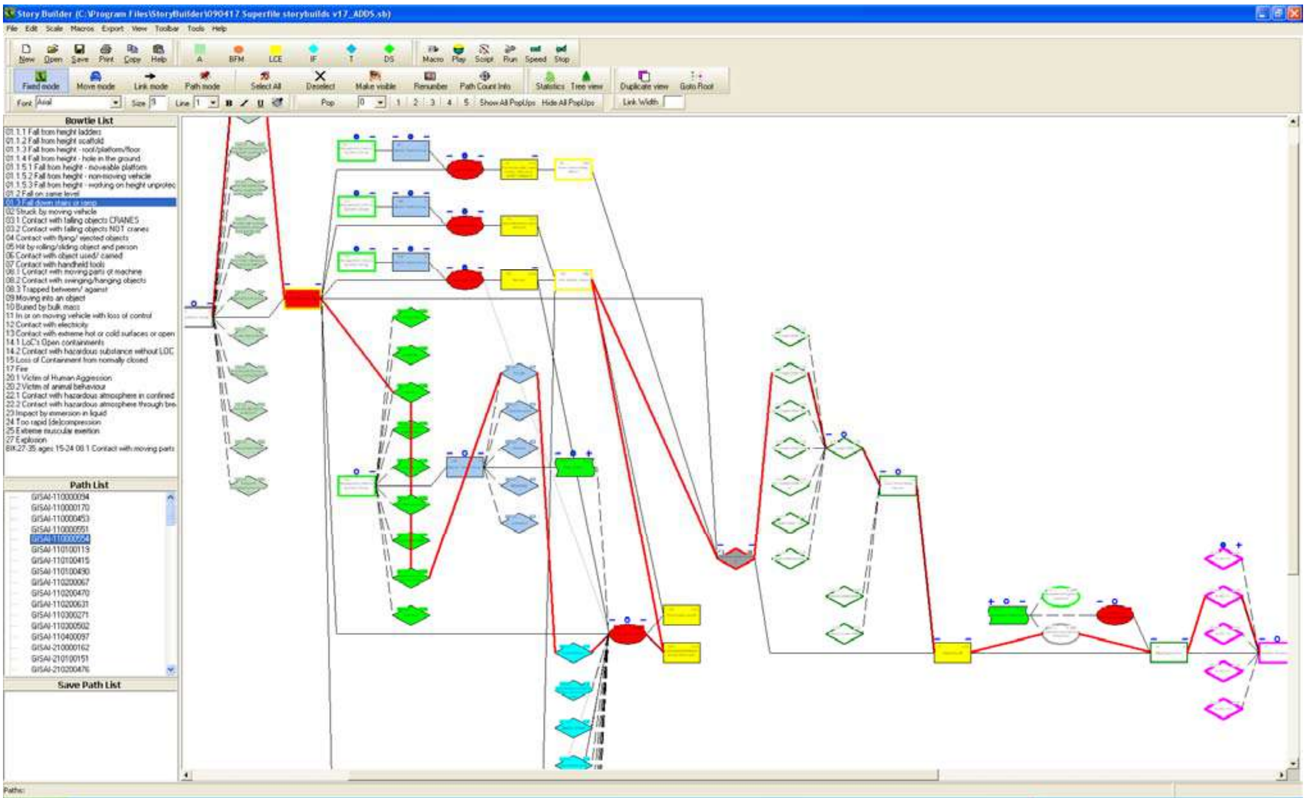

Figure 1 Interface of Storybuilder showing part of a StoryBuilder bowtie for "Fall from stairs or ramp" with a single accident pathway through the events structure highlighted.

The accidents analysed are reportable occupational accidents. Around 2000 serious accidents are investigated per year by the Dutch Labour Inspectorate (an estimated 1% of all occupational accidents, taking into account underreporting, but includes all the deaths and around 50% of hospital admissions). Data are stored in a database called GISAI (Geïntegreerd InformatieSysteem ArbeidsInspectie). It contains information on reported accidents and investigations of accidents which are reportable according to article 9 of the Dutch Working Conditions Act if they are occupational accidents resulting in serious physical or mental injury (death within 1 year, permanent injury, in-patient treatment in hospital within 24 hours).

The nature of these accidents has been described in earlier publications (Bellamy et al 2008) and reports (RIVM 2008) and extensive information about them is available on www.storybuilder.eu.

2.2 The quality and quantity of the accident data

Accident data from the Dutch Labour Inspectorate are the richest source of accident data in The Netherlands. Capture of data is for fact finding as part of a formal legal process and is extensive in that it supports this process with witness statements and detailed investigation. It is the closest one can get to what actually happened.

Information from the investigations between beginning 1998 and end February 2004 were extracted. In 2008 the data extraction still missed a quarter of the accidents, which is when the data for this paper were extracted. In 2009 the data set is complete but not fully analysed. This should not affect the relative comparisons across hazards made in this paper although it might emphasise some management delivery system factors more than others. Some statistics of the data are shown in Table 1. In the table “scenario” means a unique path through one of 36 hazard bowties modelled in Storybuilder. Total scenarios exceed number of victims because some victims are in parts of more than one bowtie and so have multiple scenarios.

Table 1: Some statistics of the Dutch reportable accident investigation data analysed and entered by the Storybuilders into the modelling system.

Statistic	Size of data set in 2008 (data in this paper)	Size of data set in 2009
Total reportable accidents analysed	9139	12656
Total victims	9409	13094
Storybuilder bowties (hazards)	36	36
Total scenarios	9580	13304
Total barriers	410	410
Number of barriers which failed one or more times	400	401
Barrier failures across barriers…..	24607	37074
…of which: Known barrier failure modes	16314	24910
Total delivery system failures…	20281	30496
…of which: Known delivery system failures	16007	25010
Known barrier task failures	16046	20236

2.3 Underreporting

It has been estimated that there is an underreporting of serious accidents of around 54%, and that this underreporting is worse for some kind of hazards than for others such as for victims of animal behaviour or human aggression (Giesbertz et al 2007). However, there is no evidence to suggest that there needs to be an extension to the 36 types of hazard covered. On the basis of underreporting it might be considered that some underlying causes have been missed. While no two accidents analysed follow exactly the same pathways through the model, it was found that within a hazard type, after 100 or so accidents had been analysed the overall structure of events remained very stable.

An update to the accident analysis database was completed in 2009 to include further accidents in the categories of contact with moving parts of machines and struck by falling object bringing the total to 12,656 accidents with 13,094 victims (Table 1). The results were consistent with the earlier analyses in that there were few additional events added to the underlying model and no new safety barriers added. These additions are not expected to dramatically change the pattern of results reported here from the analysis in 2008. There is therefore little reason to consider that underreporting indicates any serious lack of safety barrier information. The future updating of the results which are reported here using these new data is an extensive amount of work and is expected to be carried out at a later date.

3. METHOD OF ANALYSING THE DATA

Storybuilder analysts reconstructed the data of the investigation reports in Storybuilder. All the Storybuilds are kept in one file. A file can be opened in Storybuilder which contains 36 different hazard structures which include e.g. falls on the same level, numerous types of falls from heights (from ladders, roofs, moveable platforms etc), contact with objects like falling object, hanging objects, objects being carried, contact with hazardous substances, fire, explosion, human aggression, animals, and so on. (RIVM 2008, www.storybuilder.eu). This “superfile” (2008 data set in Table 1) contained around 70% of the 12656 reported accidents which had investigation reports in the period January 1998 to February 2004 inclusive. 33 storybuilds were analysed for the data for this complete 6 year 2months period. 3 Storybuilds (contact moving parts of machines, falling objects cranes and falling objects not cranes) were analysed for 2002 and 2003 only, these being the biggest accident categories. There were 9139 scenarios built into the models, these being from 9002 accidents of which a number have pathways which pass through two and sometimes 3 hazard structures. A structure consists of a bowtie shape like that shown in Figure 2 but with extensive additional information (Figure 1).

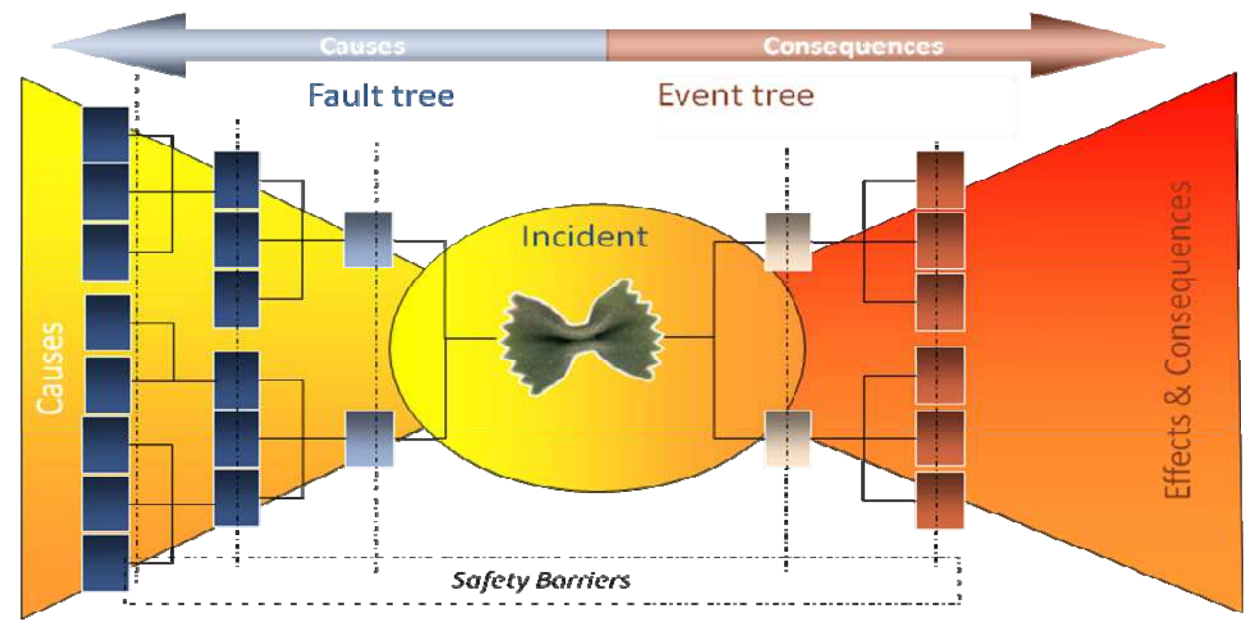

Figure 2 Bowtie

For this paper the primary interest concerns the barrier failures and their underlying causes within this structure. The fields of data to capture this in the Storybuilder database are numerous covering such things as:

- A:The activity at the time of the accident
- ET: Equipment involved
- REG: Breaches of the law
- BFM: Barrier failure modes describing the ways in which a barrier physically fails (e.g. no edge protection, victim enters danger zone)
- IF: Incident factors, which are simply extra information about the barrier failure mode (like edge protection breaks, slippery shoes)
- T: Barrier task failures (failure to provide, use, maintain and monitor the barrier)
-DS: Management delivery system failures (procedures, competence, availability, conflict resolution, ergonomics, motivation, communications)
-DDF: Dose related factors (like height of a fall)
-INJP: Type of injury and body part involved
-FO: Final consequences (death, permanent injury, recoverable injury).

The barriers and the underlying task and management factors are connected as shown in Figure 3. A single accident pathway goes through different instances of these event types, the analyst adding new types as they go along. Consequently the resulting data are very detailed. The aim is also to preserve the time sequence of the events so the "story" of the accident can be recaptured. This is for example a record of an accident of entrapment extracted from the bowties structure and going from left to right:

A|Closing door A|Using doors, hatches, etc G|Activity of victim ,G|Object of entrapment (primary) G|ESAW 01.00 Ground-level buildings and surfaces (indoor or outdoor, fixed or mobile, temporary or not) - not specified ET|01.01 Building components, structural components - doors, walls, partitions etc. and intentional obstacles (windows, etc ET|01.02.00 Doors (attached to the building) ET|Normal door G|Object of entrapment (secondary) ET|Unknown G|Environment/ location ET|Office or other building inside G|Regulations Group REG|Arbobesluit REG|Arbobesluit Art. 3.2 General requirements REG|Arbobesluit Art. 3.2 lid 1 access G|Location/ position Barrier Group 2_DS|Motivation/commitment 2_T|Operate (Use) 2_IF|Inadequate handles 2_IF|Inadequate design/ state of equipment 2_BFM|Body (part) position failure LCE|Body(part) in danger zone G|Hazardous Movement Prevention barrier group 3_DS|Motivation/commitment 3_T|Maintain 3_IF|no/ inadequate securing of hatch/bonnet or door 3_IF|Door closed by external influence 3_IF|Open door or hatch not adequate locked /secured 3_BFM|Lock(-out) and/or securing failure 5_DS|Motivation/commitment 5_T|Maintain 5_IF|No/inadequate door/ hatch opening/closing system 5_IF|No or insufficient safeguarding or other safety provisions 5_BFM|Equipment state failure 6_DS|Motivation/commitment 6_T|Operate (Use) 6_IF|External influence 6_BFM|Manual operation failure LCE|Uncontrolled movement of object/ tool (towards body (parts) CE|Trapped between/ against 8_BSM|Adequate emergency response G|Mitigation DDF|Contact- small part of body DDF|Surface of contact DDF|Crushed between objects (not being machines or vehicles) G|Dose Determining Factors INJN|N of C = 1 G|Number of casualties G|Part of body injured INJP|54 Fingers INJP|50 Upper Extremities, not further specified code G|Type of injury code INJT|040 Traumatic amputations (Loss of body parts) G|Hospitalisation HOSP|NH = Not Hospitalised G|Consequence class FOP|(Probably) permanently injured G|Absence from work ABS|unknown

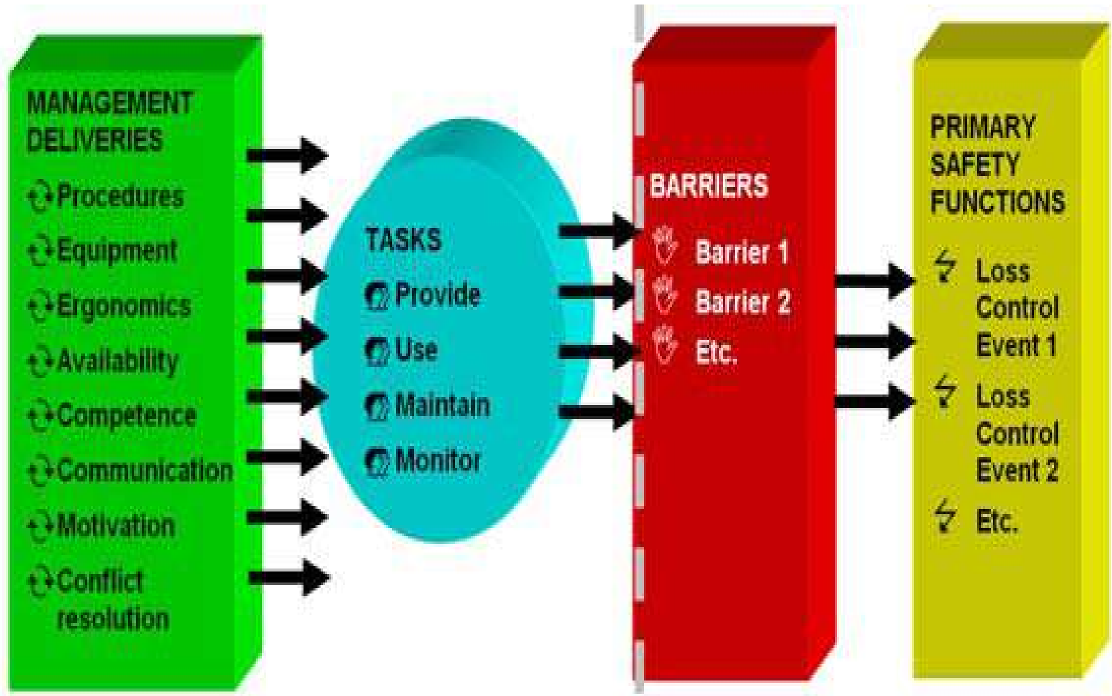

Figure 3 Management delivery systems and barrier tasks connected to barriers. When barriers fail this leads to loss of control of safety functions such as the stability of a ladder, the strength of a container.

4. RESULTS

4.1 Barrier failures

400 barriers were identified which failed in total 24,607 times comprising 16,314 known and 8293 unknown barrier failures (Table 1). Looking at individual barrier failure modes, the top failures were related to the most frequent accidents which are contact with moving parts of machines, falls from height, and falling objects. The top 10 barrier failures are shown in Figure 4 showing number of failures per year from a total of 3413 known yearly failures.

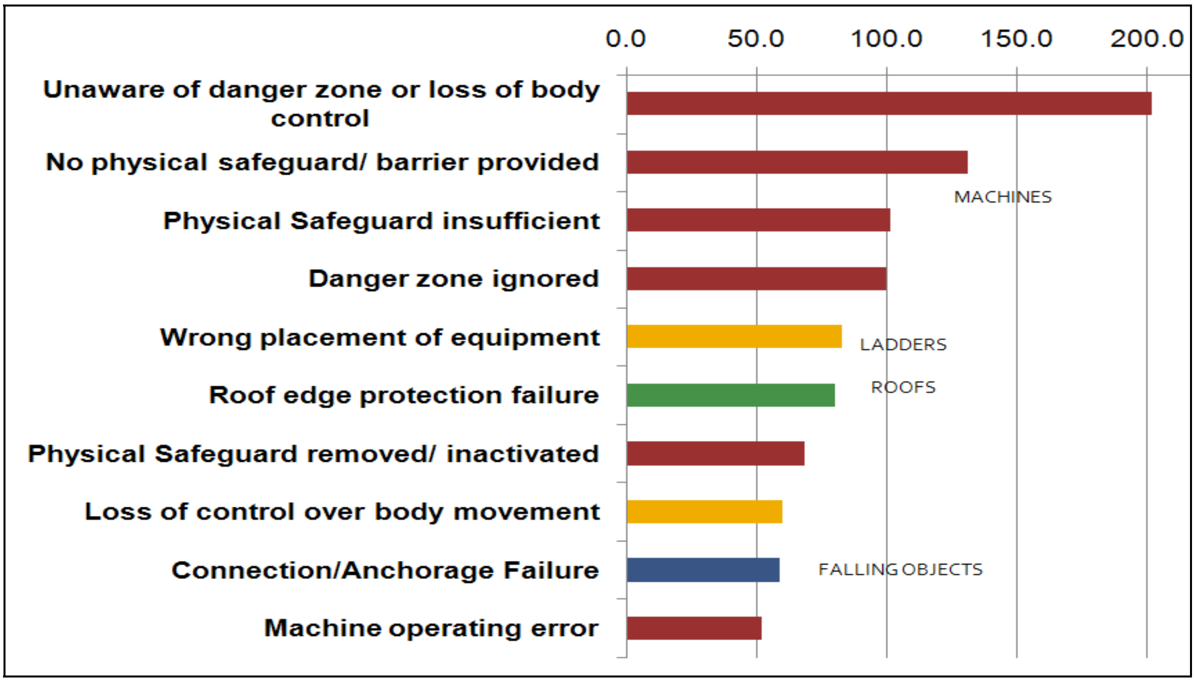

Figure 4 Top 10 barrier failures across all 36 hazards, showing number of occurrences per year. The barrier failures concern contact with moving parts of machines, falls from ladder and roofs and falling objects beause these are the most frequent serious accident types.

Mostly these are failures to physically separate a person from the danger or a person being unaware of or not respecting the danger zone of a hazard. In some cases though a person just loses physical control of their body, this sometimes being due to health problems like a heart attack, sometimes due to being knocked into or destabilized in some other way like slipping, or blown by wind. Thirdly, errors in the way equipment is used also feature in the top 10. Broadly generalising across accident types for all barrier failures from the 2008 data set (Table 1):

- Defective or failed equipment accounts for around 600 failures per year.
- Entering a danger zone (accidentally or when one should not have been there or did not need to be), when the centre event occurred or a supposedly safe zone becomes unsafe accounts for some 500 barrier failures per year.
-Ability related failures (outside a person's ability) account for around 250 barrier failures a year.
-Most of the rest appear to be control or response failures in some way related to human action or inaction but which are related to other parts of the system (e.g. the response of a piece of equipment may be unexpected, a person loses their grip on something, the victim steps onto a weak part of a structure).

4.2 Task Failures

The task failures, ignoring the unclassified ones, total 16,046. They are evenly distributed between the so-called PUMM categories of Provide (43%) and Use (45%) as shown in Figure 5 with Maintain or Monitor only being identified as failures in 7% and 5% of known cases respectively.

So, maintaining a barrier (keeping it in place and working) once it is provided and is being used is a surprisingly small proportion of the failures.

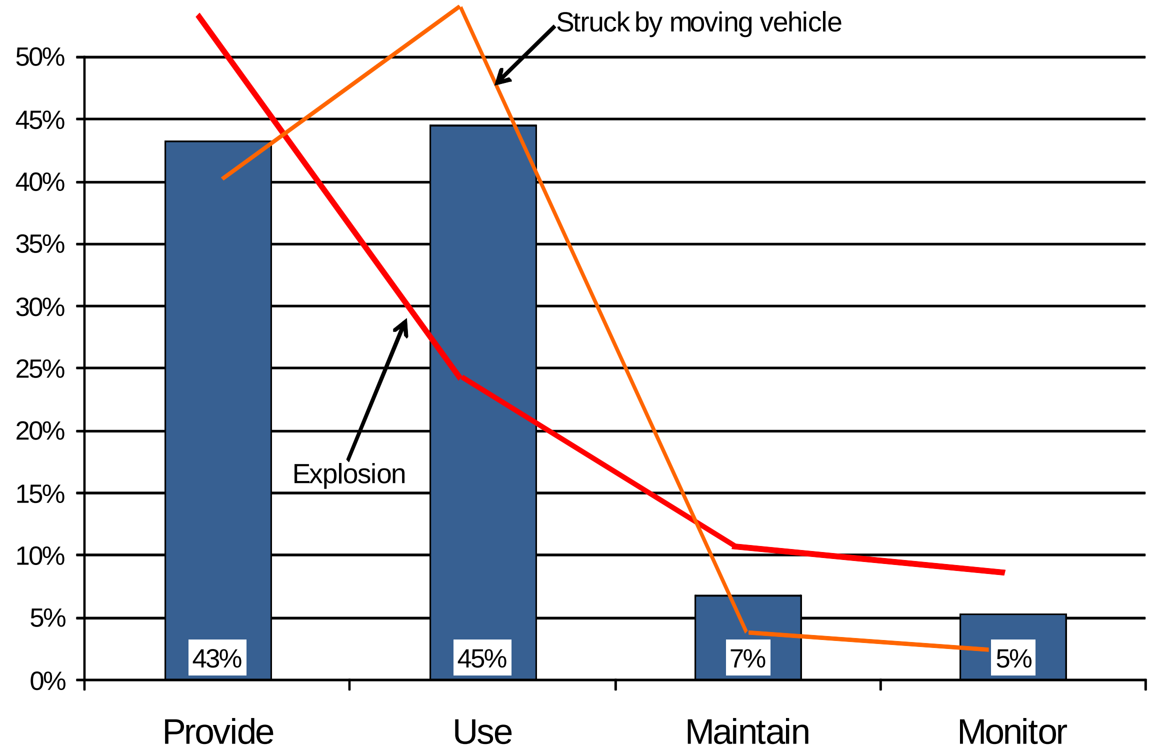

Figure 5 Provide (43%), use (45%), maintain (7%) and monitor (5%) as % of barrier task failures. Individual hazard types have different patterns, here showing struck by moving vehicle (more Use failures) and explosion (more Provide failures)

4.3 Management delivery system failures

The connection of delivery systems to barrier tasks was shown in Figure 3. Delivery system is a name for a group of resources, controls and criteria as outputs of management processes that are delivered to safety barrier tasks such that the safety barriers are kept intact (Bellamy et al 1999, Guldenmund et al 1999). These are defined for the analysis in Storybuilder as follows:

Procedures: Delivering performance criteria which specify in detail, usually in written form, a formalised behaviour or method for carrying out tasks, such as: checklist, task list, action steps, instruction manual, fault-finding heuristic, form to be completed, plan (explicit planning of activities in time).

Availability: Delivering the time or numbers of competent and suitable people to the tasks to be carried out so that people are available at the moment (or within the time frame) when the tasks should be carried out.

Competence: Delivering the knowledge, skills and abilities of the people for the execution of tasks through selection and training – delivering the right person for the job.

Communications: Delivering communications between people through various means (meetings, logs, phones, radio, visually) in order to ensure that information is delivered to the barrier task so that it is coordinated and carried out according to relevant criteria.

Motivation: Delivering motivation, commitment, awareness, alertness, attention in carrying out the barrier tasks to keep the barrier intact - delivering suitable care.

Conflict resolution: Delivering mechanisms to prioritise safety when conflicts between safety and other goals (usually production or the ease/speed/comfort of doing something) in the performance of tasks arise, including the means to avoid, recognise and resolve these conflicts.

Ergonomics: Delivering good ergonomics/man-machine interface (MMI) so that there is a good the fit between the person and the task – delivering an appropriate match between human capabilities and the demands of the barrier task including the design of equipment, tools, interfaces, layouts and their user friendliness.

Equipment: Delivering the hardware needed for carrying out the barrier tasks, including the correct equipment and tools for their use (compatibility, suitability, quality), and the availability of equipment where and when needed to carry out the task, including spares and parts needed for maintenance.

Data were analysed by summing all the delivery system failures per barrier for each of the 36 storybuilds. For reasons of wanting to first get an overview of the general patterns of failure, the delivery system data are not distinguished between the PUMM barrier task categories because it is an extensive amount of work to extract dependence information (a type of delivery system failure given a type of task failure). A task failure can have up to 3 different delivery system failures as underlying cause (a fairly arbitrary limit imposed by the building rules) whereas a barrier only needs one barrier task failure (e.g. not to use it) for the barrier to fail.

In total 20,281 delivery system failures were recorded of which 16,007 were identified. These are listed per hazard in Annex 1. Of the identified DS failures the numbers across DS categories were normalized such that the total sum of the 8 DS failures was 100% for each of the 36 hazard types.

The bars in Figure 6 show the result across all storybuilds (see also Bellamy 2009).

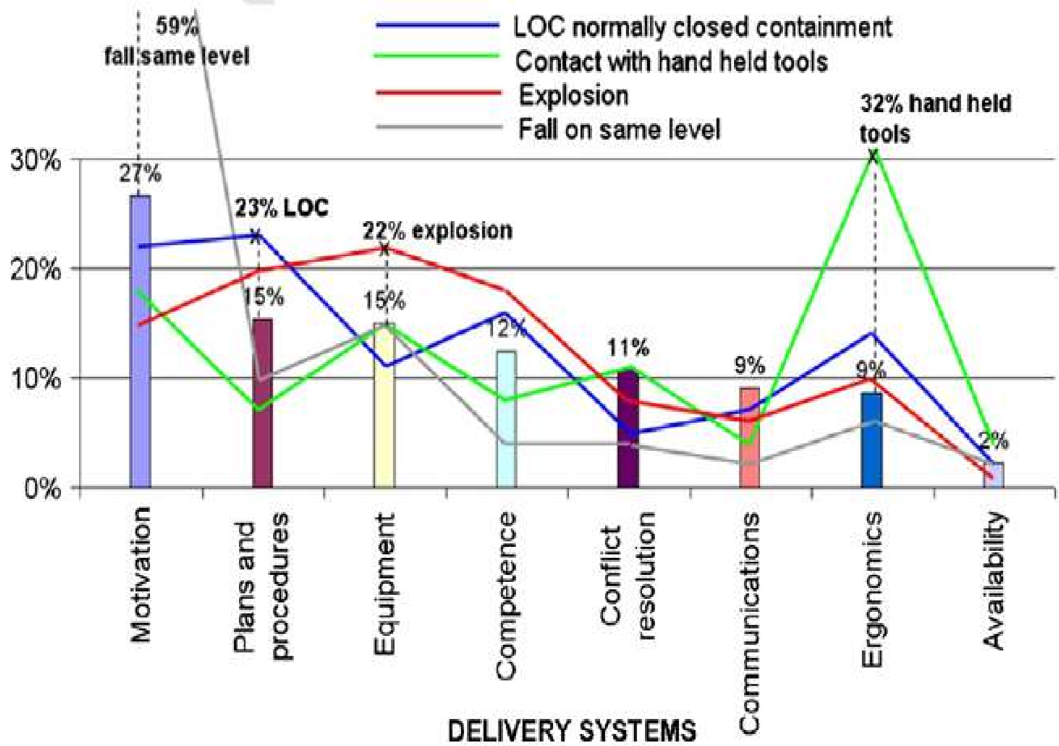

Figure 6: Across all Storybuilds the 8 delivery systems failures in order of occurrence are motivation (27%), Procedures (15%), Equipment (15%), Competence (12%), Conflict resolution (11%), Communications (9%), Ergonomics (9%) and Availability (2%). Superimposed on that are four hazards showing their deviations from the average pattern: *Fall on same level* (59% motivation), *Loss of containment* (23% procedures), *Explosion* (22% equipment), and *Contact with hand held tools* (32% ergonomics) failures.

Motivation is the top scoring DS failure followed by Procedures, Equipment, Competence, Conflict resolution, Communications, Ergonomics, Availability. Superimposed on the totals are the results for 4 different hazards, showing that different patterns are obtained for different Storybuilds. For example, Fall on same level is the top scorer for Motivation, Contact with handheld tool for Ergonomics, Loss of containment of hazardous substance for Procedures. Explosion, which scores high on Equipment, is also shown for comparison with the LOC, since both are also associated with Major Hazards (low frequency high consequence events). The implication is that different hazards require different management. Examples of different management patterns are shown in Figure 7.

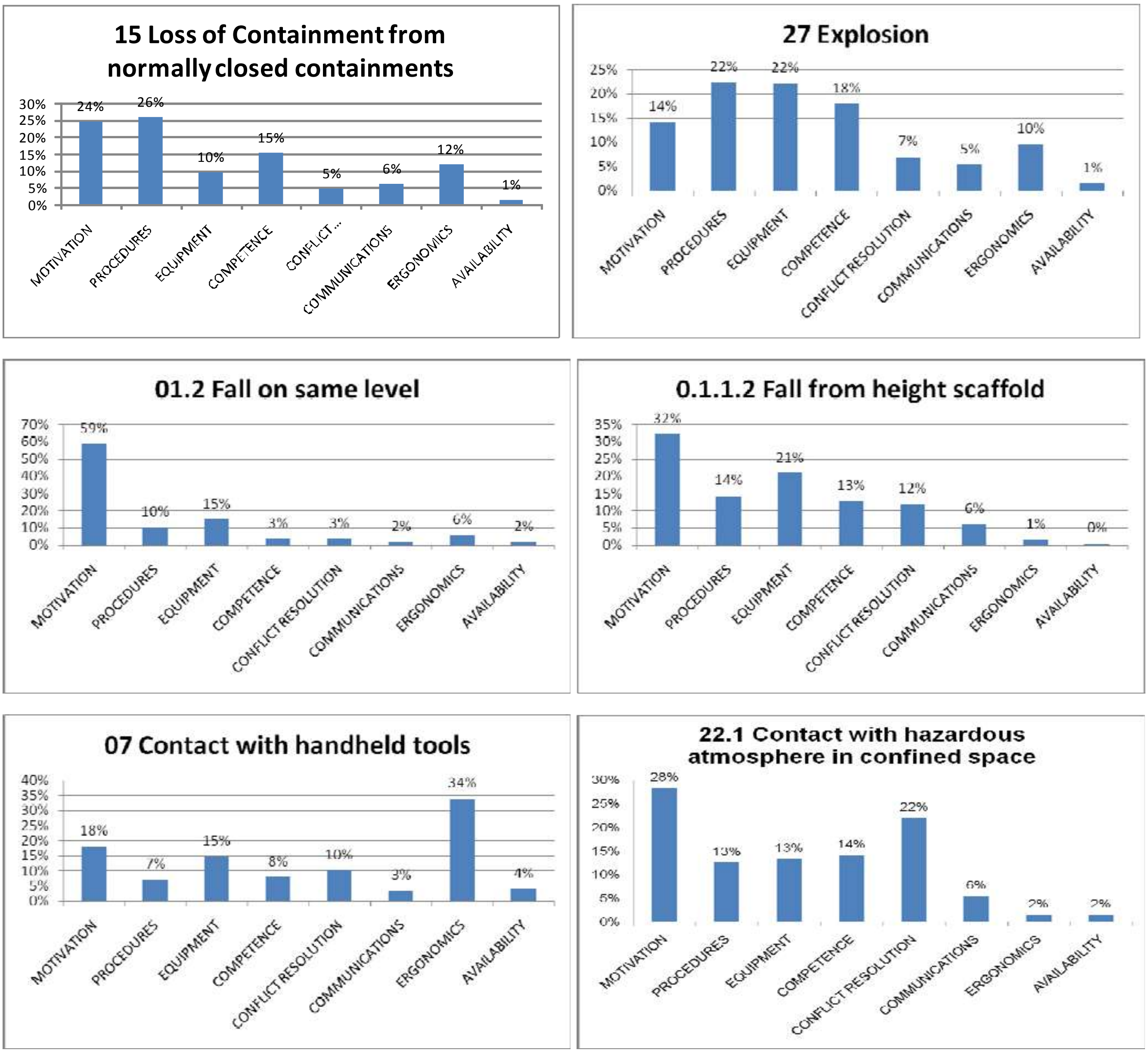

Figure 7 Comparison between hazard types to show different patterns compared to LOC

Annex1 shows the results graphically for each delivery system, emphasising the differences for the different hazards. For example procedures shows many hazards where procedure delivery failure is a common underlying cause of barrier failure, suggesting its importance in keeping a lot of barriers intact. For a particular hazard, one type of delivery might be important, whereas for another it is not. For example, hazards with high scores on Motivation tend to be low scorers on Competence failures and vice versa. On the other hand Competence and Equipment appear to be slightly positively correlated. These differences could be further explored.

5. DISCUSSION

Managements' role in managing the tasks of having intact safety barriers has been identified in over 16000 cases of barrier failures across 9142 serious accident scenarios. Looking at the 8 management delivery systems, equal chance of failing would have resulted in contributions of 12.5% for each delivery system. What is seen here are wide variations in the contributions of the delivery system failures from 59% to 0% depending upon the type of hazard. The following conclusions can be made from this first evaluation of the data:

1. Management has an important role in the prevention of incidents.

2. Depending on the type of incident it appears that certain management delivery systems are linked to certain type of incidents eg. Motivation/awareness is strongly linked to fall on the same level and struck by moving vehicle, but is important for practically all the hazards. Competence shows surprisingly relatively less importance than might have been expected but is still above the expected value for contact with hazardous substances, LOC, fire and explosion amongst others. Procedures delivery system is also important for hazards such as prevention of LOC from closed containments, buried by bulk mass, and preventing falling objects for example.

3. Connected to the conclusions of the Baker Panel report (Baker 2007) this study strengthens the observations made that there is limited connection between lost time injury (LTI) accidents as for instance due to falls from heights and LOC incidents. The observation that the low LTIs of BP is not a good metric for potential loss of containment accidents is confirmed in these results. Looking at our data, LOC indicators of the management systems should at least be including measuring awareness of risks and whether procedures are in place and being kept to.

If a company wants to manage incidents then management should consider having to address the specific hazards and the delivery systems required for their barriers rather than a more generalised level of control and feedback.

6. REFERENCES

Ale, B.J.M., Bellamy, L.J., Baksteen, H., Damen, M., Goossens L., Hale A.R., Mud, M.L., Oh J.I.H., Papazoglou, I.A.Whiston, J.Y. (2008) Accidents in the construction industry in the Netherlands: An analysis of accident reports using Storybuilder. Reliability Engineering and System Safety 93 (2008) 1523–1533

Baker J.A., (2007). The Report of the BP U.S. Refineries Independent Safety Review panel, January 2007

Bellamy, L.J. (2009) Process safety indicators: Response to Andrew Hopkins. Safety Science 47 (2009) 472-473

Bellamy L.J., Papazoglou I.A., Hale A.R., Aneziris O.N., Ale B.J.M., Morris M.I., Oh J.I.H., (1999). I-Risk: Development of an integrated technical and management risk control and monitoring methodology for managing and quantifying on-site and off-site risks. Contract ENVA-CT96-0243. Report to European Union. Available from White Queen BV, linda.bellamy@whitequeen.nl.

Bellamy, L.J. Oh, J., Ale B.J.M., Whiston J.Y., Mud, M.L, Baksteen H. Hale, A.R., Papazoglou, I.A. (2006) Storybuilder: The new interface for accident analysis, International Conference on Probabilistic Safety Assessment and Management, May 13-19, 2006, New Orleans, ASME, New York, 2006, ISBN 0-7918-0244

Bellamy, L.J., Ale B.J.M., Geyer T.A.W., Goossens L.H.J., Hale A.R., Oh J., Mud, M., Bloemhof A, Papazoglou I.A., Whiston J.Y. (2007) Storybuilder—A tool for the analysis of accident reports, Reliability Engineering and System Safety 92 (2007) 735–744

Bellamy L.J., Ale B.J.M., Whiston, J.Y., Mud M.L., Baksteen H., Hale A.R., Papazoglou I.A., Bloemhoff A., Damen M. and Oh J.I.H. (2008). The software tool storybuilder and the analysis of the horrible stories of occupational accidents. Safety Science 46 (2008) 186-197

Giesbertz,P., Eykelestam, J., Bloemhoff, A. (2007) Validatie meldingsplichtige arbeidsongevallen in het Occupational Risk Model (Validation of reportable occupational accidents in the Occupational Risk Model). Stichting Consument en Veiligheid (Consumer Safety Institute), PO Box 75169, 1070 AD Amsterdam
Guldenmund, F.W., Hale A.R., Bellamy, L.J. (1999) Development & application of a tailored audit approach to major chemical hazard sites. Proceedings of SEVESO 2000 European Conference Risk Management in the European Union of 2000: The Challenge of Implementing Council Directive 'Seveso II' Athens, Greece (available at http://mahbsrv.jrc.it/Proceedings/Greece-Nov-1999/Athens.html, Paper G3)

Haddon Jr, W. (1973) Energy damage and the 10 countermeasure strategies. Journal of Trauma 1973 vol 13 pp.321-31. Keynote address presented at the opening session of the Human Factors Society Annual National Meeting, Beverly Hills, Califomia, 17 October 1972. Reproduced in Injury Prevention 1995 vol 1 pp.40-44

Hale, A.R., B.J.M. Ale, L.H.J. Goossens, T. Heijer, L.J Bellamy, M.L. Mud, A. Roelen, H. Baksteen, J. Post, I.A. Papazoglou, A. Bloemhoff, J.I.H. Oh (2007) Modelling accidents for prioritizing prevention. Reliability Engineering & System Safety, Volume 92, Issue 12, December 2007, Pages 1701-1715OSHA (2009) EU OSHA website http://osha.europa.eu

RIVM [Dutch National Institute for Public Health and the Environment] (2008). The Quantification of Occupational Risk. RIVM Report 620801001/2008 produced by the WORM Metamorphosis consortium (NCSR Demokritos, White Queen, RIGO, Rondas, RPS, Consumer Safety Institute, Netherlands Institute for Physical Safety, HCRM Ltd, EDBC, RIVM) for the Ministry of Social Affairs, the Netherlands. RIVM, P.O. Box 1, 3720 BA Bilthoven, the Netherlands Tel+31 30 274 91 11 www.rivm.nl

Schupp, B. A., Smith, S., Wright, P. and Goossens, L. (2004) Integrating human factors in the design of safety critical systems - A barrier based approach. Human Error, Safety and Systems Development (HESSD 2004), W. Johnson and P.Palanque (Eds.), Vol. 152 (2004) 285-300, Springer

ANNEX 1: RESULTS OF DELIVERY SYSTEMS ANALYSIS

Table 2 The 36 hazard types and number of known DS failures across

Hazard	Known Management Delivery System Failures
Contact with moving parts of machine	1602
In or on moving vehicle with loss of control	1564
Fall from height - roof/platform/floor	1405
Fall from height ladders	1347
Struck by moving vehicle	949
Loss of Containment from normally closed	813
Fall from height scaffold	801
Trapped between/ against	632
Contact with flying/ ejected objects	626
Contact with handheld tools	498
LoC's Open containments	459
Contact with falling objects NOT cranes	455
Fire	418
Explosion	415
Contact with electricity	402
Fall from height - moveable platform	400
Fall from height - working on height unprotected	400
Contact with hazardous substance without LOC	381
Contact with object used/ carried	350
Contact with swinging/hanging objects	304
Fall on same level	288
Fall from height - non-moving vehicle	279
Moving into an object	204
Victim of Human Aggression	174
Contact with falling objects – cranes	157
Fall down stairs or ramp	134

Contact hazardous atmosphere in confined space	127
Fall from height - hole in the ground	111
Impact by immersion in liquid	72
Hit by rolling/sliding object	69
Extreme muscular exertion	57
Victim of animal behaviour	53
Contact with extreme hot or cold surface	23
Buried by bulk mass	20
Contact hazardous atmosphere through breathing apparatus	14
Too rapid (de)compression	4
TOTAL	**16007**

The following 8 figures show the different results for each delivery system failure.Note that hazard types with only a few DS failures accidents will have extreme low and high percentage scores

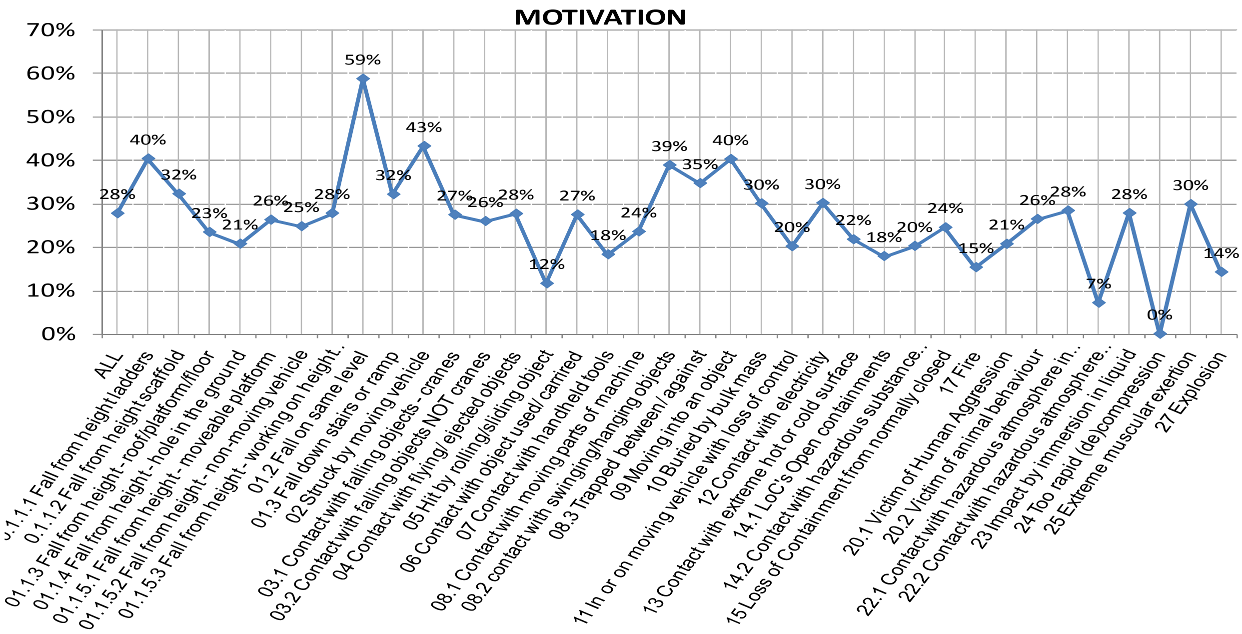

Figure 8: Motivation as % of all DS failures for each of the 36 hazards. Fall on same level (59%) and Struck by moving vehicle (43%) are the top 2. Conversely too rapid decompression (0%) and contact with hazardous atmosphere through breathing apparatus (7%) are low

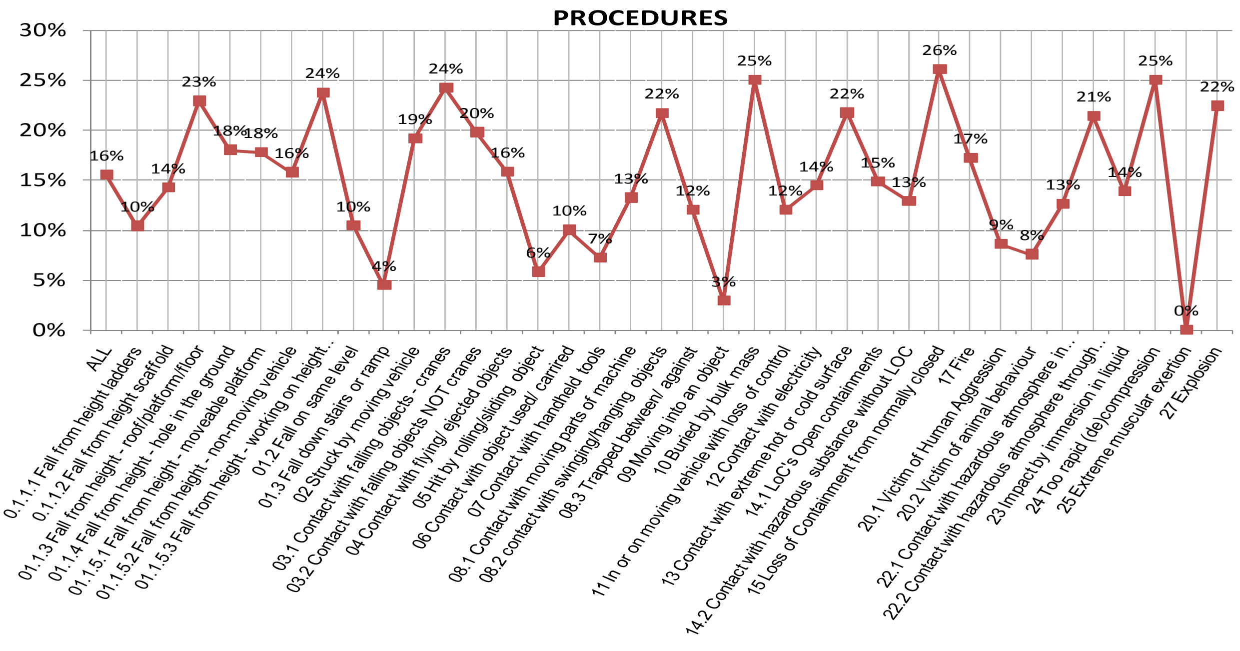

Figure 9: Procedures as % of all DS failures for each of the 36 hazards. There are a number of hazards which score comparatively high on procedures. LOC from normally closed containment (26%), Buried by bulk mass (25%), Too rapid decompression (25%), Fall from height unprotected (24%), Falling objects cranes (24%). Conversely Fall down stairs or ramp (4%), Moving into an object (3%) and Extreme muscular exertion (0%) score low

Figure 10: Equipment as % of all DS failures for each of the 36 hazards. Contact with hazardous atmosphere through breathing apparatus (29%), Too rapid decompression (25%), Explosion (22%) are the top scorers. Contact with hanging/swinging objects (3%) and Contact with extreme hot/cold surface (4%) are low scorers

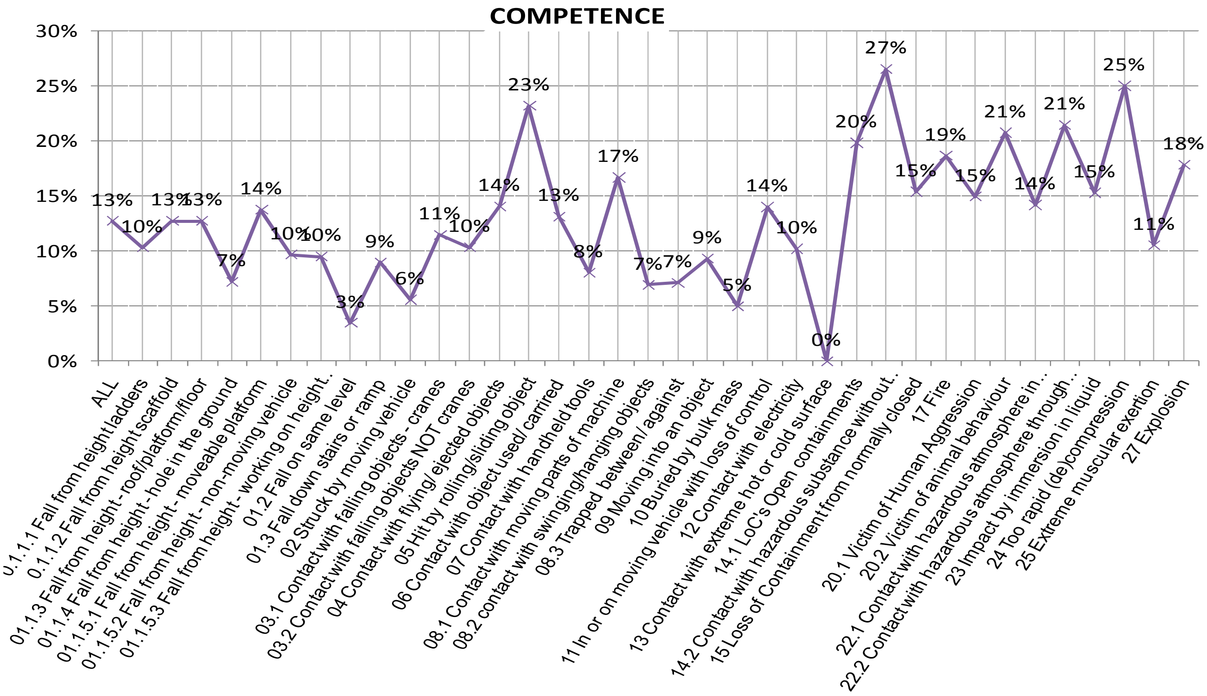

Figure 11: Competence as % of all DS failures for each of the 36 hazards. Top scorers are Contact with hazardous substances without loss of containment (27%), Too rapid decompression (25%), Hit by rolling/sliding object (23%), Victim of animal behaviour (21%), Contact with hazardous atmosphere through BA (21%). Conversely Contact with extreme hot/cold surface (0%) and Fall on the same level (3%) are low scorers

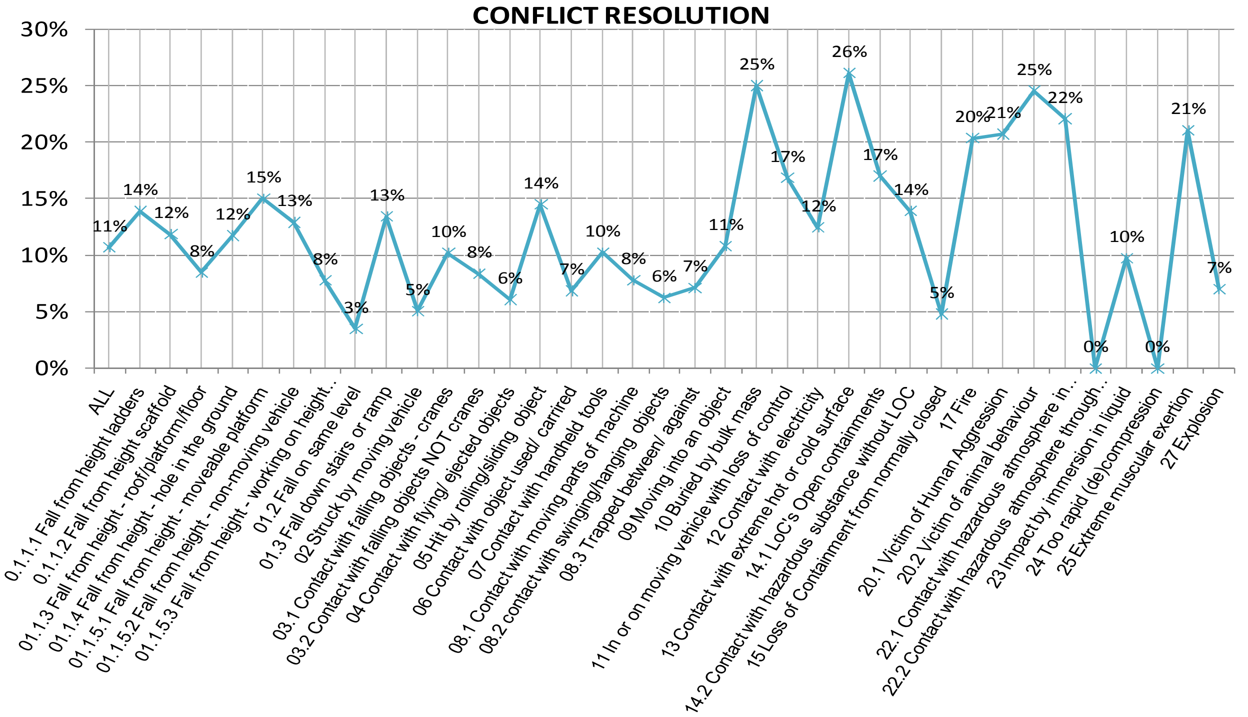

Figure 12 Conflict resolution as % of all DS failures for each of the 36 hazards. Top scorers are Contact with extreme hot/cold surface (26%), Buried by bulk mass (25%) and Victim of animal behaviour (25%). Amongst the low scorers are again Contact hazardous substance BA (0%) and Too rapid decompression (0%) as well as Fall on same level (3%) and LOC from normally closed containments (5%)

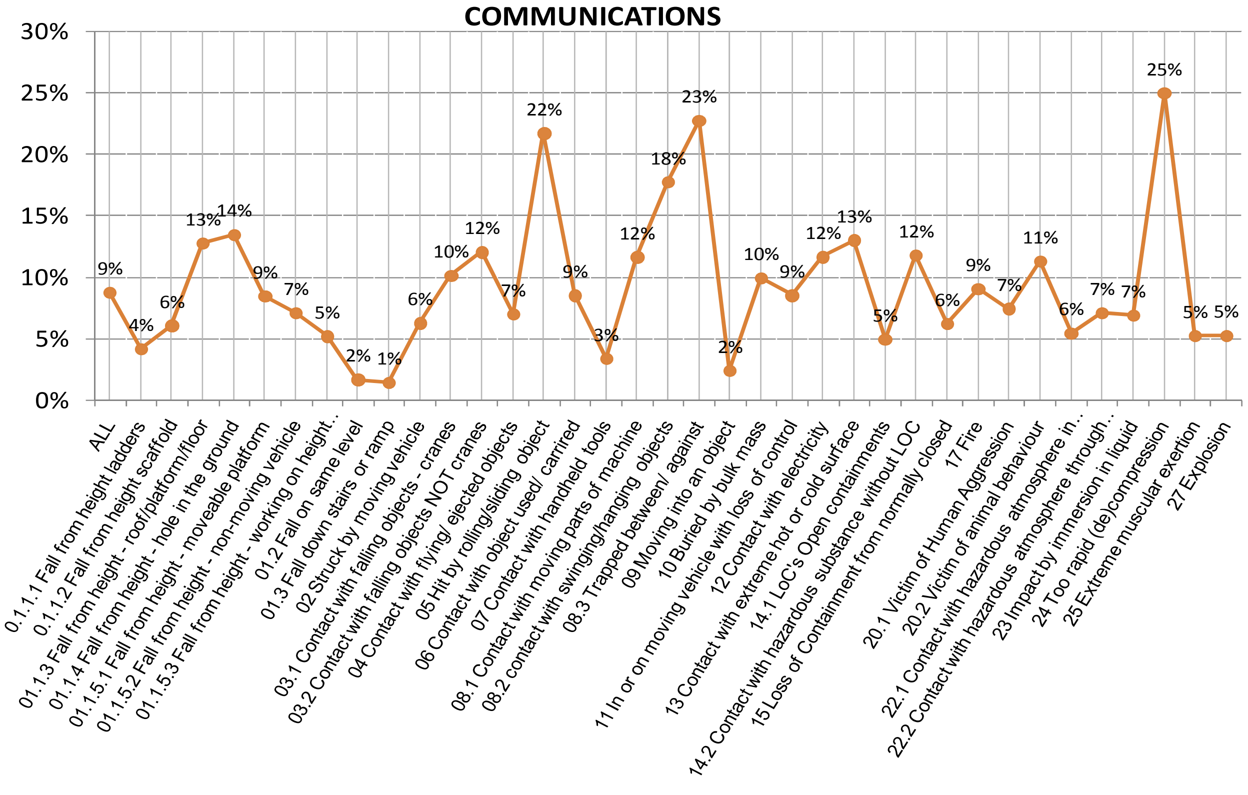

Figure 13: Communications as % of all DS failures for each of the 36 hazards. Too rapid decompression (25%), Trapped between (23%) and Hit by rolling/sliding object (22%) are top scorers. Fall down stairs or ramp (1%), Fall on same level (2%), and Moving into an object (2%) all score low.

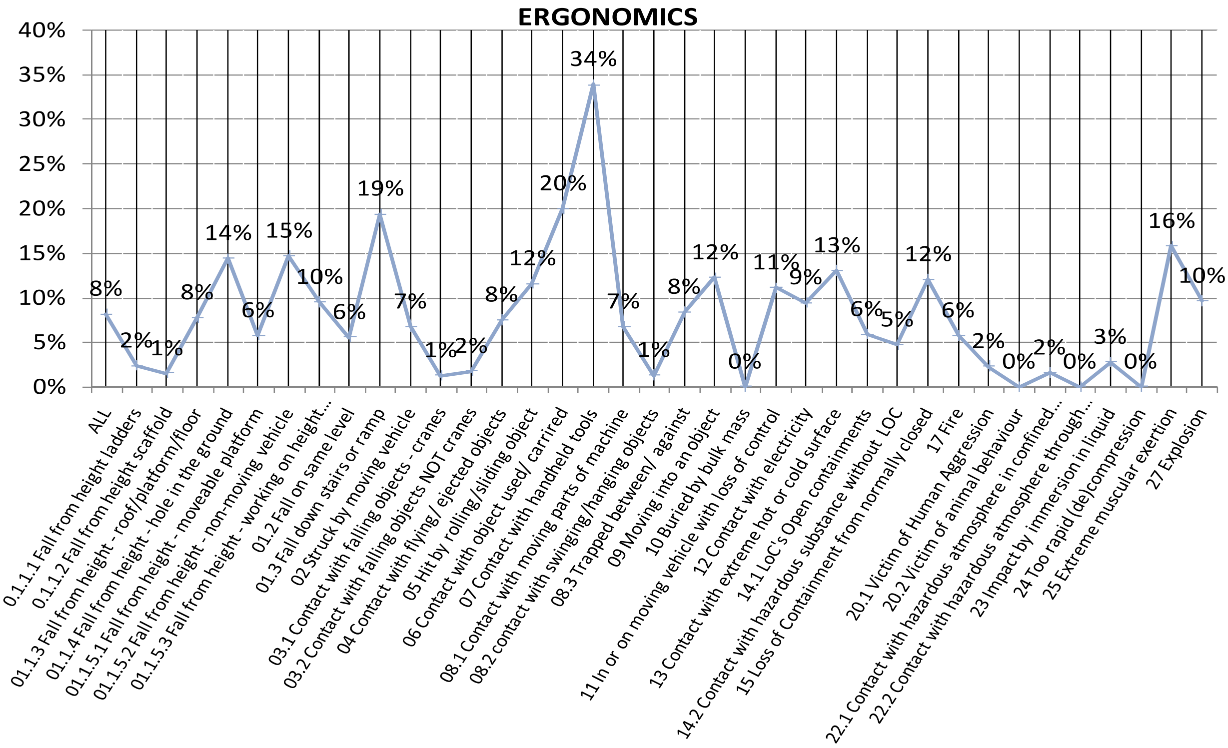

Figure 14: Ergonomics as % of all DS failures for each of the 36 hazards. Contact hand held tool is the top (34%). Low scorers include Buried by bulk mass (0%), Victim of animal behaviour (0%) Fall from height scaffold (1%), Contact falling objects cranes (1%), Contact hanging swinging objects (1%)

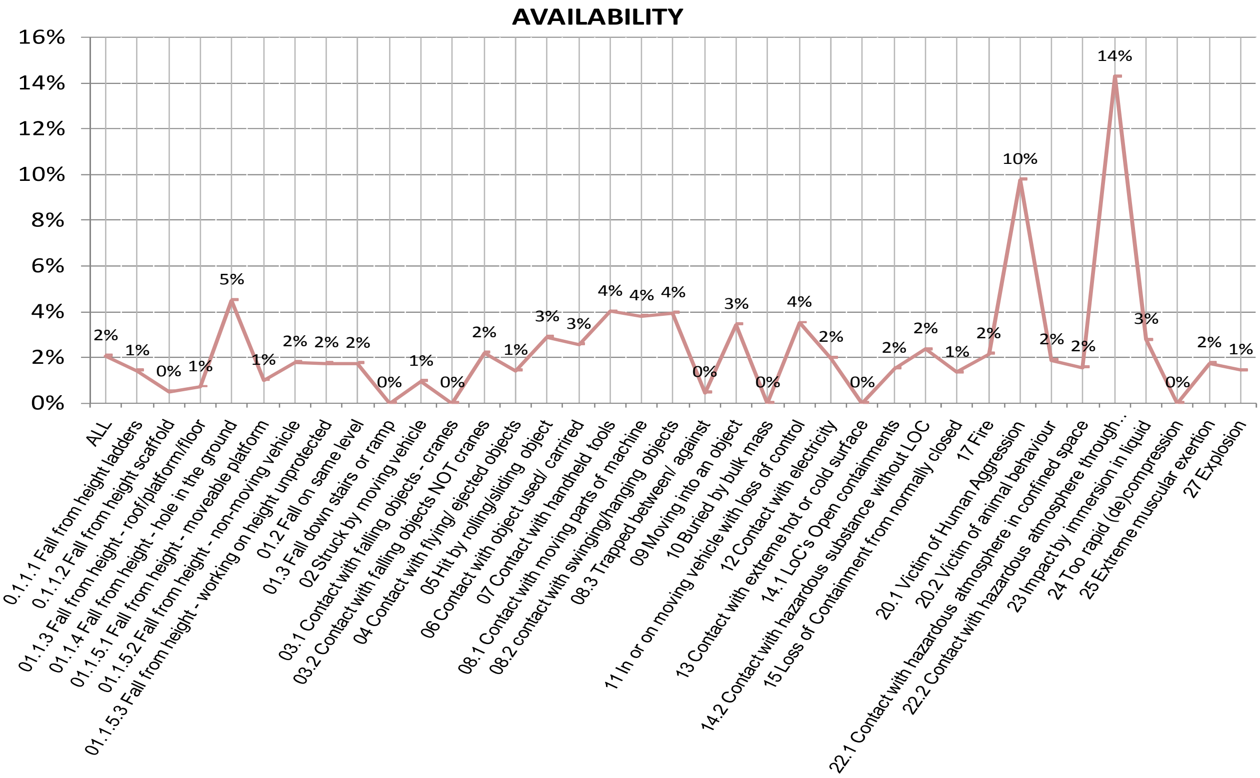

Figure 15: Availability as % of all DS failures for each of the 36 hazards. Top scorer is Contact with hazardous atmosphere through breathing apparatus (14%) followed by Victim of human aggression (10%). The others are low scorers