The Critical Role of Human Factors in Safety of Complex High-Risk Working Environments

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Safety critical environments – e.g. chemical and nuclear plants, oil and gas installations, manufacturing sites - typically present a high degree of complexity, especially in relation to the many causal interactions between technical, human and organizational elements. Such a structure poses a challenge for industrial safety, since it often produces unpredictable system behaviours that can in turn cause abnormal workers' behaviours, with an increased risk of accidents that can have even catastrophic consequences. Human factors have a crucial role in such contexts and structured behavioural interventions can have a deep impact, but their application has to take into account some prerogatives of the specific context.

The present study aims to provide a picture of how human factors impact on the safety of complex high-risk industrial sites and how the above-mentioned interactions can be modelled. Methodologies with which behavioural interventions can be re-formulated, in order to be effective in critical contexts, are outlined. In addition, attention is focused on the topic of the road transport of dangerous goods, whose critical issues still appear to be underestimated and not sufficiently regulated by European legislation. The usefulness of Resilience Engineering interventions, helping people manage complexity under pressure while aiming to reach a satisfactory safety level, is finally evaluated.

1. Introduction

Several industrial sites and working environments can be defined as "high-risk" contexts, since a very high value of the actual risk condition (R) can derive from different values of the probability (P) of occurrence of a given harmful event and the magnitude (M) of the consequent damage. This means that – when the classical risk formulation ($R = P \times M$) is applied - both very frequent low-consequences accidents and high-impact low-probability (HILP) disasters (Cozzani et al., 2014) can produce a "high-risk" condition.

However, nowadays a particular challenge is provided by HILP events, since the potentially devastating consequences of major accidents on plants and surrounding environments (e.g. major fires, explosions and toxic releases) make prevention action more and more indispensable, in addition to protection tools and appropriate emergency management strategies. At the same time, paradoxically, the low frequency with which these catastrophic events (luckily) occur typically makes them more subjected to post-accident interventions; the planning of a complete prevention activity for these particular events is not easy, mainly because in general such contexts are characterized by a high level of complexity.

To a lesser extent, even non-catastrophic accidents that produce very serious injuries (including fatalities) often require to be managed and analysed with specific criteria, as the functional safety requirements for root cause analysis of failures and incidents provided by IEC61511 (International Electrotechnical Commission, 2017). In any case, measures of injury or fatality rates (and in particular neither Lost Time Injuries) do not provide an indication about the quality of management practices for major accident risks (Anderson, 2005).

The concept of "complexity" of industrial sites is typically associable to safety critical contexts as, for example, chemical or nuclear plant as well as all plants subject to Seveso Directive (European Parliament and Council,

2012), not only in terms of high number of workers and typology of hierarchical organization, but especially in relation to the many causal connections between technical, human and organizational elements.

In particular, human factors comprise several aspects: on the one hand, human errors and the natural human tendency to initially reject the change with respect to known customs; on the other hand, the human capability to cope with the inevitable hazards, complexities, gaps, trade-offs and dilemmas that the nature of their work can help create. In complex and dynamic systems, human expertise is deemed increasingly critical for the assurance of safety (Dekker and Pitzerc, 2016). Such a multiplicity of facets of the human factor is also influenced by the local safety climate and by all issues related to human-machine interaction.

The difficulty in acting preventively in order to avoid catastrophic events is also reflected in the field of human error, where even well-known behavioural interventions (such as Behaviour-Based Safety) seem to concentrate on the 20 % of most frequently occurring items that account for 80 % of accidents, with an insufficient attention to deficiencies that are less likely to occur but have potential for catastrophic loss (Cameron and Duff, 2007).

In complex systems, the close interactions between equipment failures and behavioural errors can instead generate accidents, sometimes difficult to be detected, that can produce larger consequences (Bogard et al., 2015). Focused management of these potential accidents is what, for example, is actually officially called "Process safety management" in United States, where it is regulated through specific OSHA requirements.

The recent rise of Industry 4.0 has caused a substantial further increase of complexity in many industrial processes, for example because of the innovations based on machine intelligence, Internet Of Things and industrial automation through artificial intelligence. Such innovation can also make users have a less direct and clear vision and comprehension of system failures.

2. Modelling of complex systems safety including human factors

Realizing a risk analysis by traditional methods, which generally describe accidents by applying a sequential model representing the linear succession of a set of events linked by cause and effect (e.g. HAZOP, FMEA), can result an inadequate solution in case of complex systems (Adriaensen et al., 2019).

The causal relationships between multiple factors that characterize them can in fact be better represented through system dynamics models, which show causal interdependencies between technical, organizational and human components, generally through the graphical instrument constituted by causal diagrams.

System dynamics also takes into account the temporal dimension, since system behaviour is supposed to change over time. Moreover, while highlighting complex interactions between variables, feedback processes are often identified, in order to clarify how to discern causes and consequent effects.

In addition, such modelling can be supported by dedicated software, as the one tested some years ago in a chemical storage unit in Morocco and that was able to model the relations between variables through differential equations (Bouloiz et al., 2013). Software has the prerogative to offer the possibility to simulate different scenarios; in this way, managers are helped in taking decisions and can have a global vision of the system in an easier way, with an extended capability to preview safety issues in normal or abnormal conditions.

Between the practical implementations of system dynamics models for the causation of unsafe behaviours, the one applied by Jiang et al. (2015) – called "SD-CUB" - has shown to be able to characterize the causal structure of the system during a five-week survey and observation on a building construction project, finally generating correct patterns of behaviour. Consequently, it stimulated discussion about underlying causes of workers' unsafe behaviours and suggested specific modalities for preventing them. Constructions is an industrial field where accident rate is generally very high and, even if the potentiality of catastrophic events is reduced with respect to the sectors involving fluid mechanics, fatalities are recurrent and their prevention is hindered by complexity factors as the presence of several subcontractors.

In other cases, complex systems have been represented through automatic-controls schemes: in the study presented by Choi and Loh (2017), a feedback control with proportional-integral action has demonstrated to significantly assist in preventing industrial accidents. The current industrial safety system is modelled as a second-order G(s) transfer function including both processes and workers' behaviours, potentially producing accidents. G(s) is inserted into a closed-loop, with damping as well elastic characteristics, where any difference between the actual output and a target value is continuously calculated and consequently modified by optimizing the gains for proportional and integral actions in the feedback controller, which represents physical and social efforts to improve the industrial safety environment. The global stability of the system is finally checked through a standard root-locus analysis. The final performance is examined not only in terms of safety performance (prevention of industrial accidents) but also in a global view of costs and benefits.

3. Use of behavioural interventions in high-risk contexts

Behavioural safety approaches (and their practical implementations as behavioural interventions in working environments) are based on the concept, already identified in the 70s, that accidents are caused by unsafe acts and that safe behaviours can be induced and maintained through positive reinforcement and feedback (Chhokar and Wallin, 1984).This assumption has shown over the years to have a general validity, but it has been partially reworked and sometimes contested, especially because from many sides it has been observed that behavioural interventions must necessarily be integrated with technical and organizational solutions. In particular, Hopkins (2006) noted that unsafe behaviour is often the last link in a causal chain and not necessarily the most effective link to focus on. In many cases, engineering solutions are necessary and complimentary to behavioural solutions, when failures are unintentional (e.g. because of distraction or underestimation of the problem) but also when there are voluntary violations of the rules (e.g. for taking short-cuts). This is even more critical when major accidents are considered. Mackenzie and Holmstrom (2009) supported such an idea by making an overview of catastrophic accidents in American high-risk industries (refineries, plastics production sites, ink and paint manufacturing plants) where technical and organizational misses were proved to be the main causes of disasters. Human error appeared in fact mainly as a symptom of underlying problems, i.e. as a hardly detectable "systematic failure" related to a pre-existing fault in terms of design, manufacturing process, operating procedures, documentation or other significant factors (International Electrotechnical Commission, 2017).Consequently, behavioural interventions should adapt and be subjected to more restrictive constraints when applied in complex industrial contexts with a high risk for safety (Figure 1).
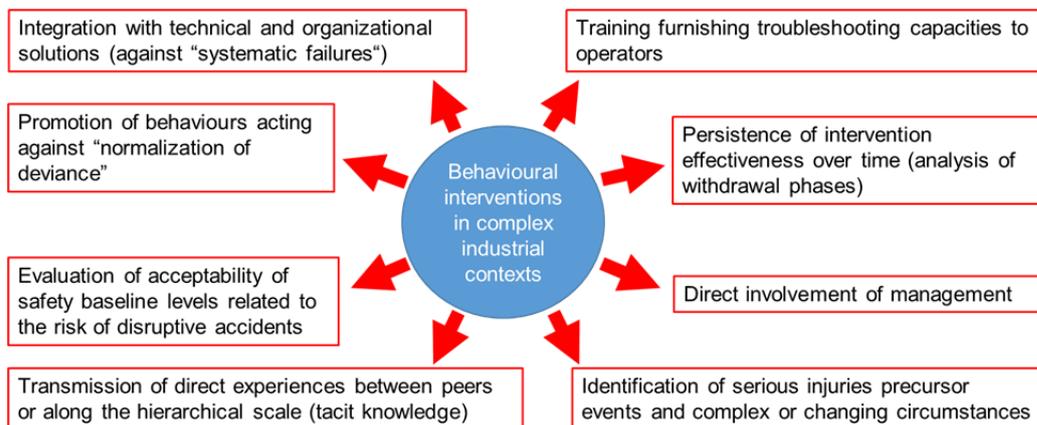

Figure 1: Main peculiarities of behavioural interventions when applied to complex industrial contexts

First, in critical environments a sure maintenance of their effects over time is fundamental: since dramatic events arise rarely, longitudinal studies, lasting even several years and including persistent interventions as well as withdrawal phases, are absolutely justified. That is why, for example, a study by Myers et al. (2010) analysed the application of behavioural safety interventions in a petroleum refinery on a time span of 20 years. Moreover, such temporal prospective can allow to identify and take into account a frequent long-term process that recent literature has identified and named "normalization of deviance": individuals or teams end up accepting a lower standard of performance ("deviant behaviours") until that lower standard becomes acceptable. For example, Bogard et al. (2015) report that in American refineries alarms are triggered whenever equipment experiences deviations beyond defined standards, but workers, after a year, start being less worried about it and reacting more slowly, with a reduction of the accepted minimum safety threshold. Behavioural interventions should therefore try to identify system factors that promote behaviours acting against normalization of deviance.Anyway, events with infrequent and unpredictable occurrence cannot be adopted as primary or unique indices of the efficacy of a safety program (Chhokar and Wallin, 1984) and interventions in complex sites should also identify, during the assessment phase, serious injuries precursor events, as high-risk tasks and behaviours, as well as complex or changing circumstances. Prevention of serious injuries and fatalities requires a dedicated action plan, even by involving safety professionals, in charge of reviewing all the controls for the specific task. In behavioural interventions, the risk of disruptive accidents can modify the standard evaluation criteria for baseline levels: e.g., Azadeh and Fam (2009) report that an initial 41.8% of unsafe behaviours was considered as unacceptable in a steel manufacturing company because of the risk of very serious consequences.

The respective roles of workers and leaders are also fundamental for behavioral interventions in major hazard sites. Operators have to be fully prepared to deal with all conditions, including process abnormalities, through a training furnishing troubleshooting capacities, even in front of residual risks arising from not identified hazards (Anderson, 2005). Tacit knowledge (Podgorski, 2010), for example in the form of transmission of histories of direct experiences between peers or along the hierarchical scale, can be another useful instrument to increase skills. Management – and not only front line personnel – should be directly involved in such process, with consequent increase of the company safety culture and creation of a satisfactory safety climate.

4. Modern challenges related to uncertainty and variability factors in critical safety contexts

In the last decade, the complexity of many industrial contexts has further increased because of the development of smart technologies and new communication instruments that have accompanied the growth of the fourth industrial revolution, together with many factors of unpredictability that can cause abnormal workers' behaviours, finally producing an increased risk of accidents. Engineering and computer innovations have produced new typologies of human–machine and human-technology interactions in order to complete operations more rapidly and with better production performances. In Europe, the Machinery Directive (European Parliament and Council, 2006) states that each machinery manufacturer, when designing and constructing machinery and when drafting the instructions, must envisage not only the intended use of the machinery but also any reasonably foreseeable misuse thereof, also taking into account the level of general education and acumen that can reasonably be expected from the involved operators. Such human component should be also taken into account when electrical or electronic control systems for machines, as defined by IEC 62061 standard (International Electrotechnical Commission, 2015), are designed as functional safety systems. Indeed, this constitutes a further element of variability in already complex systems such as those under study and represents a specific challenge for safety maintenance in modern critical working environments. EU Agency for Safety and Health at work identified that complexity of new technologies produces a transformation of work processes and, if accompanied by poor design of human–machine interfaces, can lead to increased mental and emotional strain on workers (Adriaensen et al., 2019). Human reliability assessment (HRA) techniques, where human cognition is assessed the same way as technical failure, i.e. by decomposition of systems and assignment of probabilities to sequential cause–effect events, has a limited validity in such cases. The human error probability is not, anyway, the only cause of action failures: the variability of the context where workers operate is fundamental, since human performance is highly context-sensitive (Hollnagel, 2005). The present study aims also to underline how road transport of dangerous goods (e.g. Liquefied Petroleum Gas or other flammable products) should be considered as critical as fixed installations in terms of safety. Their risk levels are in fact comparable in terms of potential disruptive character of accidents and in both cases the risk analysis appears particularly complex. Transport follows an itinerary with boundary conditions varying in time and in space, with a high degree of variability and unpredictability and with a considerable number of daily transports, even with trans-national character. Sometimes, a significant lack of knowledge about the vulnerability of targets over such large areas can emerge. If the contents are released or exploded, there can be significant damage to people, environment, infrastructure and surroundings, even via a domino effect. There are risks due to the technical reliability of the vehicles, road safety and - to a greater extent than in the fixed industrial sites - to the human factor (e.g. level of training, experience, tiredness, distraction).

The frequency of accidents and type and extent of the consequences are similar, but for fixed plants there is a specific regulation concerning a systemic risk analysis for major accidents, i.e. Seveso III Directive (European Parliament and Council, 2012), whereas instead the road transport of dangerous goods in Europe is only regulated by the ADR Agreement (Economic Commission for Europe inland transport Committee, 2019). Such difference in the applicable regulations represents a potential deficiency in safety of European transport.

On the road, in addition, solutions for mitigating the adverse effects of an accident are typically more difficult to be applied with respect to fixed installations. Carpignano et al. (2009) describe the concept of multi-risks analysis, as it was successfully applied in an Italian project where seismic risk, industrial risk, risk in transportation of dangerous goods and hydro-geological risk were simultaneously analysed and mapped.

Due to the significant impact of human factors on transport, over the years several behavioural interventions have been applied especially to truck drivers. Generally, subjects are classified based on their age and their years of work experience, since these data can influence the willingness to accept to submit to rules and change habits. In many cases, a feedback technique is applied with the help of a technology that informs the worker about his/her safety performance through graphs or simple alarms. A recent study by Pereira de Oliveira et al. (2019) describes the use of an Event Data Recorder system on trucks. It underlines that the technology alone can reduce the occurrence of undesired behaviours, but a follow-up training and an ongoing

feedback given by managers (based on their analysis of the data on each driver) are critical to prevent the behaviour patterns revert to those observed in the undisclosed monitoring phase. Similarly, other studies show the importance of additional face-to-face or telephone coaching. Moreover, even in the presence of automatic safety technologies, the supervisory control carried out by the driver is not simply a passive action, but an active phase including many cognitive tasks (Banks and Stanton, 2019).

In transport, as well as in other critical contexts represented by many industrial sites, such capacity of coping with complexity under pressure, while keeping in mind the job performance targets, can be synthesized with the expression "Resilience Engineering". The term "resilience" actually includes different disciplines (engineering, social sciences like psychology or sociology, biology, etc.) that study safety in complex environments at the same time (Martínez-Córcoles et al., 2011). It also reflects the ability of a system to absorb shocks and facing change and uncertainty in the long term, even though a vision of systems as a whole, with a holistic approach (Adriaensen et al., 2019). Starting from the assumption that past success does not represent a guarantee of continued safety for the future (Dekker and Pitzerc, 2016), in resilient systems organizations have to remain sensitive to the possibility of failure and to continuously work on the ability to deal with unexpected events. As well as management has a dominant role in determining the actual risk in high-hazards sites, leaders should also be the major actors of resilience and have a direct involvement in behavioural interventions, especially because the culture of an organization is largely determined by leaders' behaviour (Hopkins, 2006). According to the extreme variability and unpredictability of complex systems, leaders should understand that their own behaviours can change in time, while facing new challenges, and that being a leader is not a fixed personality trait (Martínez-Córcoles et al., 2011) but rather a dynamic attitude towards unexpected events. That is why behavioural interventions should address behaviours at all levels of the company hierarchical scale, including front line workers, foremen, supervisors, middle managers and top managers, also considering that leaders influence their employees by means of safety climate. In practical cases, managers and supervisors may, therefore, be themselves subjected to behavioural interventions, whose methodologies can be specifically modified in order to give importance to leaders' role. Martínez-Córcoles et al. (2011), for example, retrace the characteristics of a pre-existent empowerment approach and highlight how the function of leaders is to increase (by means of their behaviour) the team's potential for self-management. This result can be reached through an exemplar commitment to their own work, a decision-making style that guarantees members participation, a good coaching capability, a strong commitment to disseminate company mission and, finally, an intense participation to employees' concerns. Accelerating such a change in leadership behaviours has shown to produce a robust safety improvement in behaviours at all organizational levels.

5. Conclusions

Prevention of high-impact low-probability disasters represents a not trivial challenge in safety of complex industrial sites and requires dedicated methodologies for both contextual analysis and consequent interventions. Human factors (including lacks such as individual errors, but also potentialities related to interpretative, monitoring and adaptability skills) cannot be neglected, but at the same time they cannot be seen as an exclusive intervention scope. Most recent modelling schemes agree that it is necessary to keep taking into account other factors (as equipment/engineering failures and organizational issues) and nowadys industrial sites are increasingly represented as dynamic systems varying over time. Multidisciplinary approaches, such as Resilience Engineering, have the potential to help in managing such a complexity.

The present research shows that, in these contexts, behavioural interventions need to include specific topics (as knowledge and management of processes' abnormalities) and that the persistence of their effectiveness over long periods has a prior significance. In particular, very serious consequences of accidents require a dedicated action plan (with a stronger participation of hierarchy starting from foremen and supervisors) and safety baselines, even for levels generally considered "low", can become unacceptable if they refer to behaviours with a high-risk of producing fatalities or catastrophic consequences. The importance of a strong involvement of companies' leaders - either through direct participation to behavioural interventions or through the awareness that their own role needs to vary with time and in response to unexpected challenges- is also underlined. The present work finally aims to warn that, in Europe, a regulatory shortcoming can be hypothesized in the context of the transport of dangerous goods, since it consists in mobile complex systems which can cause environmental disasters, while lacking an adequate organic risk analysis system, which is typical in Seveso sites instead. Moreover, humans-technologies interaction is very frequent in behavioural interventions on drivers, but it does not cancel the person's active role in terms of monitoring and potentially erring in unpredictable contexts. The analysis originates from evaluations mainly related to the transport of liquids, but it can be extended to other types of materials.

References

Adriaensen A., Decré W., Pintelon L., 2019, Can complexity-thinking methods contribute to improving occupational safety in industry 4.0? A review of safety analysis methods and their concepts, Safety, 5(4), art. n. safety5040065.

Anderson M., 2005, Behavioral safety and major accident hazards. Magic bullet or shot in the dark?, Process Safety Environmental Protection, 83(B2), 109–116.

Azadeh A., Mohammad Fam I.M., 2009, The evaluation of importance of safety behaviors in a steel manufacturer by entropy, Journal of Research in Health Sciences, 9(2), 10-18.

Banks V.A., Stanton, N.A., 2019. Analysis of driver roles: modelling the changing role of the driver in automated driving systems using EAST, Theoretical Issues in Ergonomics Science, 20, 284–300.

Bogard K., Ludwig T.D., Staats C., Kretschmer D., 2015, An industry's call to understand the contingencies involved in process safety: normalization of deviance, Journal of Organizational Behavior Management, 35(1-2), 70-80.

Bouloiz H., Garbolino E., Tkiouat M., Guarnieri F., 2013, A system dynamics model for behavioral analysis of safety conditions in a chemical storage unit, Safety Science, 58, 32–40.

Cameron I., Duff R., 2007, A critical review of safety initiatives using goal setting and feedback, Construction Management and Economics, 25(5), 495-508.

Carpignano A., Golia E., Di Mauro C., Bouchon S., Nordvik J.-P., 2009, A methodological approach for the definition of multi-risk maps at regional level: first application, Journal of Risk Research, 12(3–4), 513–534.

Chhokar J.S., Wallin J.A., 1984, Improving safety through applied behavior analysis, Journal of Safety Research, 15(4), 141-151.

Choi G.H., Loh B.G., 2017, Control of industrial safety based on dynamic characteristics of a safety budget-industrial accident rate model in Republic of Korea, Safety and Health at Work, 8(2), 189-197.

Cozzani V., Antonioni G., Landucci G., Tugnoli A., Bonvicini S., Spadoni G., 2014, Quantitative assessment of domino and NaTech scenarios in complex industrial areas, Journal of Loss Prevention in the Process Industries, 28, 10-22.

Dekker S., Pitzerc C., 2016, Examining the asymptote in safety progress: a literature review, International Journal of Occupational Safety and Ergonomics, 22(1), 57–65.

Economic Commission for Europe inland transport Committee, 2019, European Agreement concerning the international carriage of dangerous goods by road (ADR). New York and Geneva: United Nations.

European Parliament and Council, 2006, Directive 2006/42/EC of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast), Official Journal of the European Union, L 157, 49.

European Parliament and Council, 2012, Directive 2012/18/EU of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC, Official Journal of the European Union, L 197, 55.

Hollnagel E., 2005, Human Reliability Assessment in Context, Nuclear Engineering and Technology, 37, 159–166.

Hopkins A., 2006, What are we to make of safety behavior programs?, Safety Science, 44, 583-597.

International Electrotechnical Commission, 2015, IEC 62061. Functional safety of safety-related electrical, electronic and programmable electronic control systems.

International Electrotechnical Commission, 2017, IEC 61511. Safety instrumented systems for the process industry sector.

Jiang Z., Fang D., Zhang M., 2015, Understanding the causation of construction workers' unsafe behaviors based on system dynamics modelling, Journal of Management in Engineering, 31(6), art. n. 04014099.

Mackenzie C., Holmstrom D., 2009, Investigating beyond the human machinery: a closer look at accident causation in high hazard industries, Process Safety Progress, 28(1), 84-89.

Martínez-Córcoles M., Gracia F., Tomás I., Peiró J.M., 2011. Leadership and employees' perceived safety behaviours in a nuclear power plant: a structural equation model, Safety Science, 49(8-9), 1118-1129.

Myers W.V., McSween T.E., Medina R.E., Rost K., Alvero A.M., 2010, The implementation and maintenance of a behavioral safety process in a petroleum refinery, Journal of Organizational Behavior Management, 30(4), 285-307.

Pereira de Oliveira L., Morais Lemos B., Vieira da Silva M.A., Jiménez Alonso F., da Silva Guabiroba R.C., 2019, Analysis of the event data recorder system regarding criteria of safety, operation and consumption in a Brazilian trucking company, Transportation Research Part F: Traffic Psychology and Behaviour, 65, 630-642.

Podgorski D., 2010, The use of tacit knowledge in occupational safety and health management systems, International Journal of Occupational Safety and Ergonomics, 16(3), 283–310.