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Sociotechnical systems resilience: a dissonance engineering point of view

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Abstract: Resilience deals with the capacity to adjust itself face disturbing events, to cope with unforeseeable conditions. Resilience is based upon the dynamic process of "visual piloting". The gap between the specified task and the done activity generates dissonance between beliefs and representations. In many cases, such as silent migration or normalization of deviance, management of dissonance is hazardous. The proposition of this article deals with a resilient management of dissonance. The case study expresses the management of dissonance in the context of railway accident.

Keywords: Socio-technical system, Safety, Resilience, Dissonance management, Railway.

1. INTRODUCTION

A sociotechnical system is designed to run inside its specified design and safety margins (DOD 2012). Factors of context as well as the system's environment evolve and vary, affecting sociotechnical system's performance. In this case, the sociotechnical system runs outside its specified design and its safety margins. The gap between the specified task and the real activity generates dissonance between beliefs and representations. The article differentiates, on one side, the hazardous management of dissonance, such as silent migration or normalization of deviance, and, on the other side, the resilient management of dissonance. The article proposes two solutions for a resilient management of dissonance. The case study expresses these two types of management of dissonance in the context of a railway accident.

2. STATE OF THE ART: SOCIOTECHNICAL SYSTEMS RESILIENCE

2.1 What does resilience mean?

Luzeaux (Luzeaux, 2011) characterizes resilience as a "management at the border of the domain of application. The challenges linked to resilience include the management of that which is uncertain or unplanned, accidents, the transition between more or less catastrophic circumstances while avoiding a true catastrophe, and the return to a more normal operational status". Here, the term of resilience relates to the sociotechnical systems including the traditionally three levels: the technical system level, the human level and the organizational level (a crew, for example). Luzeaux (2011) differentiates four main resilience functions: 1) avoidance (capacity for anticipation); 2) resistance (capacity for absorption); 3) adaptation (capacity for reconfiguration), and 4) recovery (capacity for restoration).

In short, resilience relates to the sociotechnical system's capacity to adjust faced with disturbing events, to adapt and learn, when the disturbances are apart from the specified perimeter of the system adaptation mechanisms, i.e. irregular threats and threats without precedent. Moreover, resilience includes the detection that the adaptive capacity limits are reached (Luzeaux, 2011). Such adjustment capability has to maintain safety and avoid accident.

This adjustment capability is based upon the dynamic process of "visual piloting". The system must have a great capacity to estimate its position with regard to the danger zone (Luzeaux, 2011). The system must be designed to cope with uncertainty. It is necessary to specify the envelope of required, desirable, even acceptable, execution and to require that the system recognizes the situations where it is likely to leave this envelope. "Resilience is obtained *via* the system capability to monitor conditions at the edges of the performance envelope, determining their value and the usual distance from the edge and the ability to adapt the operational behaviour of the system to potential developments in the envelope…" (Luzeaux, 2011). This capacity is based upon architecture flexibility and tolerance. The objective is to qualify and quantify the drift of the system towards the state of failure before a major breakdown occurs.

In many cases, the system has been designed to be safe under specified conditions, but there are no means to monitor the system when it operates under unspecified conditions, and to reassess actual risk. Safety under this situation is neither monitored nor controlled. This is like visual piloting without visibility. We describe three kinds of unspecified conditions:

barriers removal, silent migration, normalization of deviance. They may be modelled as functional resonance.

Vanderhaegen (2003) explains how human operators deviate and bypass barriers (functional, physical, procedural…) which were designed and built by safety engineers. Pressure to increase performance, as well as negative impacts of barriers (increase operator workload), cause barriers removal or bypassing. In the context of Benefit/Cost/Deficit (BCD) analysis, the operators neglect the safety and dangerous consequences of barriers bypassing. It is partly due to cognitive biases that highlight performance benefits while veiling and hiding hazards. The BCD analysis can be a way to define resilience indicators and criteria in order to assess the impact of behavioural alternatives facing perturbations such as barrier removals (Zieba et al., 2009, Zieba et al., 2010, Zieba et al., 2011).

On the one hand, since the barriers have been removed, the system moves silently, migrates, outside its safety specified conditions. Amalberti (2009) makes it clear that safety devices, by reducing system performance, generate deviating behaviours from operators in order to maintain the specified performance level. In the case of an automatic drug dispensing system, the migration phenomenon can begin very quickly as far as the deployment step. Amalberti (2009) explains that "*the nurses, with the complicity of the doctors, created false patients to remake wild drug stocks for all marginal cases*" which are the cases where "*the patient is not yet recorded in the database", or "situations of losses of pill in geriatrics*". The perverse effect of the research of safety is induced by the reduction of adaptive capability, which becomes more powerful within the specified perimeter, but more rigid and extremely fragile outside this perimeter, in case of sharp context variation. This migration phenomenon is excluded from the experience feedback process; it is dumb, in some extent an omerta situation (code of silence).

On the other hand, barriers removal and running outside safety specified conditions become normal. Vaughan (1996) defines normalization of deviance as gradual process and incremental deviations where unacceptable practices or standards become "acceptable risk", allowing risk to increase over time. As management recurrently observes the problem with no consequence, one gets to the point that the problem is normal and acceptable. This behaviour becomes the normal way of doing business. Those who try to challenge the behaviour are ignored or stigmatized. The lack of casualty provides evidence proving the success of this deviant behaviour.

These situations may be modelled as functional resonance. The Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012) expresses the interaction between performance variability of the output (O) of functions. It is induced by the variability of the functions' input (I), time (T), control (C), resources (R) and preconditions (P) (fig. 1).

Unwanted outcomes are due to interaction among individual functions, unusual variability out of the range of everyday variability (Hollnagel, 2012). For each of these elements, variability is described in terms of speed (too fast / too slow), distance (too far / too short), sequence (reversal / repetition / commission / intrusion), object (wrong action, wrong object), force (too much / too little), duration (too long /too short), direction (wrong direction) and timing (too early / too late / omission). Sources of variability are external or internal of the system, such as working environment, ambient operating conditions, organizational culture, as well as maintenance quality or equipment reliability and availability.

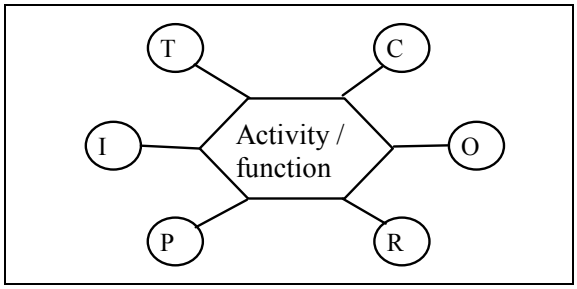

Fig. 1. Functional representation with FRAM (Hollnagel, 2012).

2.2 Dissonance engineering

Dissonance engineering applies the cognitive dissonance concept and denotes the discomfort, the conflict, when simultaneously holding two or more conflicting representations, beliefs, or values. The dissonance generates misunderstanding, frustration, anger. People reduce dissonance by altering existing cognitions, avoiding situations or information sources that disconfirm ones' beliefs, rejecting different knowledge, or adding new ones to create a consistent belief system (Festinger, 1957). Dissonance theory explains human behaviour by positing that people have a bias to seek consonance between their expectations and reality. People engage in a process termed "dissonance reduction", which can be achieved in one of three ways: lowering the importance of one of the discordant factors, adding consonant elements, or changing one of the dissonant factors (Festinger, 1957).

Dissonance engineering applies this notion in order to explain, on the one hand, the conflict of representations between groups, and, on the other hand, conflict between behaviours and representations. Such conflicts can arise from BCD analysis.

Dissonance engineering consists of exhibiting these differences and conflicts between sets of representations and beliefs, in order to reduce these conflicts, to change beliefs, to restore a clear and relevant situation awareness, to enhance hazard avoidance, to limit compensation phenomena, and to improve adaptation capability.

The dissonance management aims at returning to a new level of knowledge stability, the reduction of the dissonance. Trial-and-error, and wait-and-see are strategies to manage dissonance (Vanderhaegen, 2013).

3. PROPOSITION: DISSONANCE MANAGEMENT FOR RESILIENT SYSTEMS DESIGN

There is always a difference between the real behaviour and the specified behaviour of the system. This variation is seldom expressed. More still, the work of engineers, in term of reliability, of risk prevention, is based primarily on the specified behaviour, never on the real behaviour.

Hardy (2010) expresses that "plans that do not reflect reality may create the impression that effective organization is in place and that risks have been reduced, when in fact large risks could exist".

This difference may grow from the beginning of the operation of the system, from step to step. This gap generates difference between, on the one hand, the beliefs of the designers and the managers (high level and middle management), on the other hand, the beliefs of the operators. Two different cultures, two different sets of representations, and beliefs, are formed in an insidious way then, in opposition one of the other. There is, on the one hand, the set of representations and beliefs that the managers, the engineers, the quality managers and the quality auditors forge themselves; the specified path, the system as-designed, the task as-prescribed. The designers and the managers believe that the system is operated compliantly with the specified procedures, regarding the safety regulations. On the other hand, there is the set of representations and beliefs which the operators work out, the actual path, the system as-used and the activity as-done (Leplat, 1985). For instance, operators tend toward more barriers removals. Since the difference between the real behaviour, the task, and the specified behaviour, the activity, of the system grows, the dissonance grows accordingly.

These two sets of representations, of beliefs, are dissonant. They give different meanings to the events, with the situations of the environment, the actual states of the system, insofar as these two sets of representations are based on two different reference marks. This dissonance refers to inconsistency or conflict from holding two or more incompatible beliefs or representations simultaneously.

The figure 2 expresses this difference between these two behaviours. The specified path deals with the specified task (Leplat, 1985), or the work-as-imagined, in the context of FRAM (Hollnagel, 2012), taking place along the time. It contains specified local variability included within tolerance margins, that is everyday, or 'normal' variability (Hollnagel, 2012) as defined *a priori*.

The actual path, among other possible ones, denotes the actual activity (Leplat, 1985), or the work-as-done (Hollnagel, 2012), of the sociotechnical systems, function of met contingencies. This actual path contains actual local variability, since these contingencies are not stable and linear.

The gap between these two paths is due to unusual conditions, 'out-of-range' variability (Hollnagel, 2012), that is not an isolated case, but a huge trend. These unusual conditions may be new and unforeseeable working environments conditions.

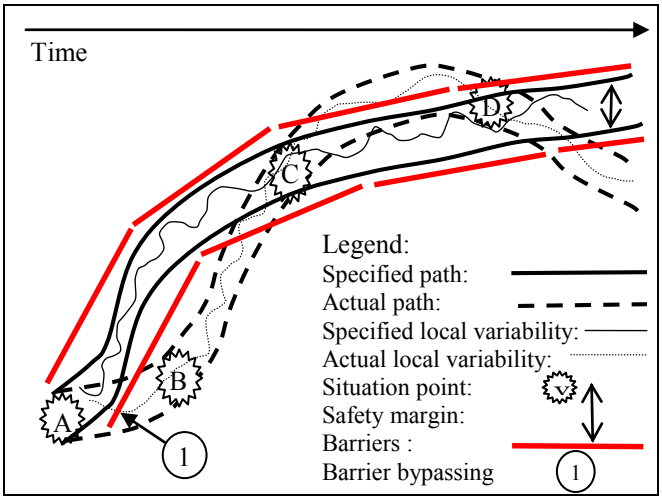

Fig. 2. Specified and actual paths of a sociotechnical system.

Coming from A, this actual path crosses the barrier at 1 (figure 2) and moves to B, then to C. The actual path from A to C *via* B expresses a deviation that may be far away from the specified path. This deviation may be due to performance variability outside the specified range, including evolution of the environmental situations. It may be based upon BCD analysis. The difference between the specified behaviour and the real behaviour is compensated by the operators by various means, like withdrawal of barriers, new unwritten procedures, or quite simply the standardisation of the deviance. The exceptional practices, which comprise risks or which are to be implemented in only exceptional situations, become current, regular, routine, and their risked character, is hidden by the banality of the practices, the routines. Mostly, this deviation phenomenon deals with silent migration. No one can assess the distance, the gap, between the specified and the actual paths; there is no situation awareness, no capability to assess the risk induced by the situation point B. It is a visual piloting, but without visibility.

One can differentiate two kinds of dissonance management: the hazardous one and the resilient one.

The hazardous or pathogenic management of the dissonance deals with processes or procedures change that may be made without understanding of the increase of risks (Hardy, 2010). These changes can produce uncontrolled new hazards.

The hazardous or pathogenic management of the dissonance lays on:

- The silent migration which is invisible and uncontrolled. It is a denial of the gap between the specified path and the actual one.
- The normalization of deviance, which reinterprets the gap as consistent with the regulations and uses the exceptional procedures of the regulations as usual ones.

- The search of the scapegoat, in order to avoid a deeper analysis of the situation.

In a state of dissonance, managers will avoid information and situations that might increase the dissonance. So they may restore consonance through misperception, rejection or refutation of the information that is incompatible with their beliefs and representations. In this context, this variation, product of variability, is denied in the representations of the managers and the engineers, since these representations interpret this variation like a failure or an error which one should hasten to correct. Moreover, support is sought from others who share the same beliefs, and attempts are made to persuade others, in order to restore consonance. These means allow management to reaffirm already held beliefs and representations rather than reference material that contradicts them.

On the other hand, the resilient management of dissonance consists of exhibiting these two sets of representations, expressing incompatibilities between them, suggesting means to change beliefs, and to restore a common clear and relevant shared understanding of the situation from the two communities (managers and operators). The aim is that all stakeholders, operators as well as managers and designers share the actual states of the system, and how far the actual states of the system are from the specified ones, in order to explain hazardous situation and to reduce the dissonance.

The resilient management of the dissonance is based upon:

- A clear, relevant and shared situation awareness, among all the communities, operators as well as management and regulation, which implies to assess the gap between the specified path and the actual one as usual fluctuations or, on the opposite, the trend of a forecast latent deviation.
- The simulation of possible or incredible accident scenarios, function of the context, and the actual states of the system produced from, on the one hand, an accident cases base, and, on the other hand, field data provided by relevant sensors.
- The consideration of assessed evolutions in order to update the design of the system, comprising safety design (barriers, procedures …) and to restore safety, including the evolutions of the system's environment (Bachatène, 2008).

In this context, we develop two solutions in this article, the first on expressing migration against risk, the second on training to avoid and to cope with unpredictable accidents. Then, we propose to use FRAM to model the variability.

3.1 Mistake-proving device for resilient management of dissonance

The first solution is based mostly upon mistake-proving devices, such as one which assesses and expresses to the operators and the managers the gap between both paths, and persuasive technology devices (Fogg, 2009).

For each most important risk, an HCI panel expresses the risk assessment matrix (table 1), and the actual risk assessment. Since barriers removal, as well as silent migration or normalization of deviance modify the behaviour of the system, actual risk is different from the specified risk. We propose to enlighten this difference and exhibit it to stakeholders.

Severity / Probability	Catastrophic	Critical	Marginal	Negligible
Frequent	High	High	Serious	Medium
Probable	High	High	Serious	Medium
Occasional	High	Serious	Medium	Low
Remote	Serious	Medium	Medium	Low
Improbable	Medium	Medium	Medium	Low
Eliminated	Eliminated			

Table. 1. Risk assessment matrix (DOD, 2012)

We propose that the panel expresses the migration of the actual risk on the matrix. For instance, barriers removal impacts risk that passes from medium to high. In this context, the first step consists in enhancing the vigilance in order to avoid risk. Then, as a second step, a new risk mitigation has to be done in order to reduce the risk.

This panel has to be deployed upon operators' workstations as well as upon managers' ones. This solution allows all stakeholders to share a relevant representation of actual risks.

3.2 Foreseeable possible or incredible accident based upon simulation

The second solution consists in presenting possible or incredible accidental scenarios to operators and managers (figure 3). The simulation expresses scenarios of possible or incredible accident that may happen, function of the actual path of the system. The simulation enhances the shared situation awareness and gives the opportunity to foresee potential accident.

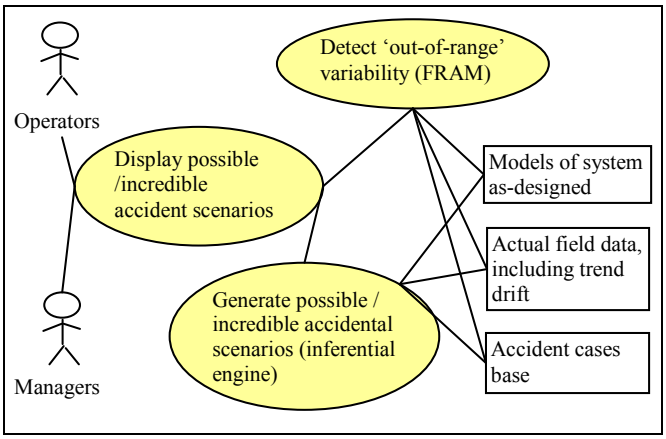

Fig. 3 Foreseeable possible or incredible accident.

These scenarios are elaborated from actual field data on the one hand, and the accident cases base on the other hand.

3.3 Modelling variability and the gap between specified task and actual activity with FRAM

Both these solutions express the gap between specified task and actual activity, that is quite a huge variability. FRAM (Hollnagel, 2012) models this variability, and interaction between functions that finish as an accident.

The figure 4 expresses the 'normal' variability (Hollnagel, 2012) of the function F3's output, depending on variability of its input (F1) and control (F2). The variability of the function F3's output impacts function F4 since it is one of its inputs. The main issue is to detect and model the drift from normal variability to 'out-of-range', hazardous, variability that induces accident. The lying "S" expresses resonance or variation within a function that affects its output and, then, the downstream functions.

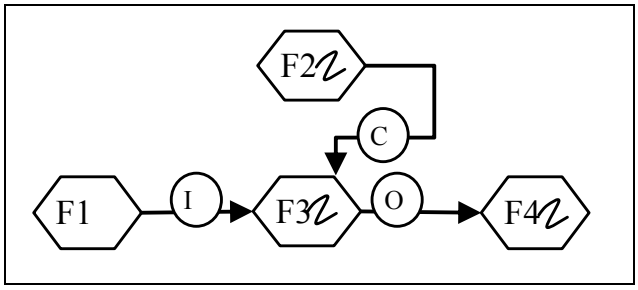

Fig. 4. Generic example of functional resonance analysis method.

4. CASE STUDY: RAILWAY ACCIDENTS ANALYSIS

The application deals with the dissonance management in the railway context. It is based upon the analysis of the Zoufftgen accident report (BEATT, 2009). On October 11th, 2006, two trains collided head on near of Zoufftgen. Six people died, one was seriously injured and fifteen others had minor injuries.

The report expresses many direct and indirect causes or causal factors of the accident, that are (BEATT, 2009):

- the human error: the Traffic Controller of the Bettembourg Central Control Post (CCP) mistakenly issued the driver of the Regional Express Train an order to pass through the "danger" signal protecting the section of track on which the freight train was travelling;
- the mistake issuing the pass-through order, and which concerns the CCP: the incorrect staff handover procedure just before the accident, the high frequency of signal faults, the poor ergonomics of the available documentation, and the ergonomics of the Visual Control Panel which could be improved;
- the failure of attempts to rectify the situation: incorrectly pressing the radio warning button, delay in implementing the traction power cut-off procedure, failure to transmit the warning to the Thionville Control Post, and the limited capacity of the telephone system at the Bettembourg CCP;
- underlying causes regarding staff skills: insufficient knowledge by the CCP staff of the procedures to be followed, particularly for issuing pass-through orders or for handling emergency situations, and the absence of practical training in emergency procedures;
- the Safety Management System and the regulatory framework of Luxembourg Railways (CFL): unrealistic division of tasks between the Bettembourg CCP staff, lack of encouragement to gain experience and laissez-faire approach to monitoring staff and implementing management control. The Area Manager and his Assistant said that they were surprised at the extent of non-compliant behaviour at shift handovers.

4.1 Hazardous management of dissonance contributing to the accident

In many instances, this case study shows that hazardous management of dissonance is implemented.

The report shows normalization of deviant behaviours:

- The Traffic Controller did not carry out all the prescribed preliminary checks before issuing a pass-through order. This omission seemed to occur fairly often at the Bettembourg CCP since the wrong-track working fixed equipment display is not in the Traffic Controller's visual field when he is looking at the check lights for the tracks towards France (BEATT, 2009).
- Written orders to pass through a main fixed signal, a "danger" signal. At Bettembourg, 107 written orders to pass through a Main Fixed Signal were issued over the three-month period, before the accident. The cause was unknown in most orders (BEATT, 2009).

The report shows silent migration, too:

- Violation of staff handover procedure, due to poor procedure usability. At 11h30, the Morning Traffic Controller wanted to leave but the Evening Traffic Controller had not yet arrived. This quite common practice is contrary to the regulations. In addition to the oral handover, the Morning Traffic Controller gave a sheet of "scrap paper" to the Evening Train Announcer (BEATT, 2009).
- Lack of separation between traffic management activities and ordering food activities, in order to prepare lunch. It is a hidden dual-task consuming attention resources to the detriment of the traffic control activity (BEATT, 2009).

The report shows impacts of factors of context:

- Poor usability of the visual control panel. There are two different meanings expressing track availability (BEATT, 2009).
- Poor usability of regulation books. The book prescribing handover procedure exhibits a poor usability, staff members didn't read the procedure and developed their own one (BEATT, 2009).
- High frequency of signal faults. It is not unusual that the main fixed signal fails to set at "proceed" when a route command is made (BEATT, 2009).
- Low reliability of the devices attempting to rectify the situation. The radio warning signal failed, due to a hidden fault on the device (BEATT, 2009).
- Lack of knowledge about the traction power. "The CCP staff did not know that the button to cut off traction power only operates on the marshalling yard track and has no effect on the main tracks" (BEATT, 2009).
- Lack of efficient communication at the staff handover (quality of the communications between operators) (BEATT, 2009).

4.2 Modelling interaction of the variability generating the accident with FRAM

These elements are modelled using functional resonance method.

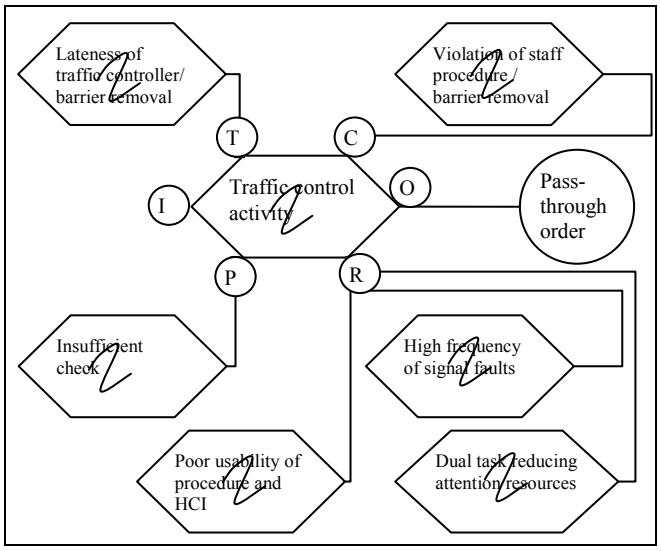

Fig. 5. Functional resonance model of the accident.

The figure 5 expresses the interaction of the variability, using the functional resonance analysis method. The pass-through order, which is the output (O) of the traffic control activity, is induced by many elements, the violation of staff procedure (C: control), the lateness of the evening traffic controller (T: time), the insufficient check (P: precondition), and, mostly resources (R: resources) difficulties, dual task reducing attention resources, high frequency of signal faults, poor usability of procedure(s) and HCI.

The managers and the operators didn't share a common situation awareness of the activities as done, at Bettembourg, generating dissonance between representations and beliefs of these two communities. The managers didn't know the extent of non-compliant behaviour at shift handovers (BEATT, 2009). Normalization of deviance as well as silent migration were the usual hazardous management of dissonance at CSF. No one was able to detect that the adaptive capacity limits were reached, nor to estimate the system position with regard to the danger zone. There were neither safety margin nor tolerance capability.

In this context, both the avoidance (issuing a pass-through order) and the resistance (attempting to rectify the situation) functions of the resilience failed.

On the opposite, the resilient management of dissonance would satisfy the functions of the resilience, mostly avoidance and resistance in order to estimate the actual position with regard to the danger zone.

4.3 Mistake-proofing device restoring the capability to visual piloting for resilient management of dissonance

The avoidance function consists of restoring the capability to visual piloting, rather than piloting without visibility (silent migration and normalization of deviance). It consists in detecting the trend and expressing the gap between the specified task and the real activity. A clear and relevant situation awareness must be shared among all the actors of CSF, operators as well as managers and regulation (Ruault et al., 2012a, Ruault et al., 2012b). This clear shared situation awareness is based upon feedback from field, expressing the gap between specified procedure and done activity. This shared situation awareness lays on the presentation of the actual risk face to the specified risk.

Severity / Probability	Catastrophic	Critical	Marginal	Negligible
Frequent	High	High	Serious	Medium
Probable	High	High	Serious	Medium
Occasional	High	Serious	Medium	Low
Remote	Serious	Medium	Medium	Low
Improbable	Medium	Medium	Medium	Low
Eliminate	Eliminated			

Accident

1 2 3

Table. 2. Applied risk assessment matrix to express migration

This normalization of deviance may be expressed using risk assessment matrix. Written orders are exceptional barriers removal that have to be used in situations where an accident is improbable. Such trends, as issuing written orders have to be detected, expressed to all stakeholders in order to be fixed. From step to step (table 2), few written orders were used in situations where an accident is remote (1), then more written orders were used, reaching occasional likelihood (2), then more and more written orders, around 100 written orders per month, reaching probable likelihood (3), passing from

medium risk to serious risk, then high risk. The visual display expresses explicitly this migration.

4.4 Expressing foreseeable possible or incredible accident to operators

The avoidance function is based upon a simulation that expresses to operators the accident that should happen within the actual context. This simulation complements the visual display expressing explicitly the current migration. It is based upon field data and accident cases base. It matches the field data, such as written orders, with the accident cases and expresses incredible and unpredictable accident to operators.

The resistance function consists of maintaining the capability to rectify the situation. It relies on secure equipment reliability, such as radio. It is based upon relevant and well known skills to cut off traction power, knowing the perimeter and the limits of the button (marshalling yard track), to phone to the operators who are able to cut off the traction power. The resistance function has to be efficient along track between Bettembourg and Thionville, whatever the location of the train.

6. CONCLUSIONS

To adjust to disturbing events, to cope with unforeseeable conditions, resilience capacity is based upon the dynamic process of "visual piloting". There is always a difference between the specified task and the done activity. This gap generates dissonance between beliefs and representations. In many cases, such as silent migration or normalization of deviance, management of dissonance is hazardous and does not avoid accident. The proposition of this article deals with a resilient management of dissonance that allows expressing this gap and enhancing shared situation awareness in order to restore visual piloting capacity. The case study illustrates the management of dissonance in the context of railway accident. The case study addresses silent migration and normalization of deviance contributing to an accident.

FRAM differentiates 'normal' variability and 'out-of-range' variability, but does not model the trend, the drift, nor these two kinds of variability. It will be a key issue to enhance FRAM in order to model trend and express these two kinds of variability.

This first step, enhancing visual piloting, has to be completed with a second step in which the gap has to be taken into account. That means upgrading the system function of the new environment conditions and the identified trend, modifying the safety device, both physical, functional as procedural, and evolving training, in order to implement a culture of safety.

This after-the-fact approach is the first step in order to prepare an open-ended experiment. We will compare the dissonance engineering approach with other ones in order to highlight its relevance in a resilient perspective.

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