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Human capability to cope with unexpected events

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SSM perspective

Background

In the light of the Fukushima accident, it stood clear that the challenge of the unexpected is of great importance to both regulators and licensees. For SSM, as for many other national regulators, there was a self-evident need to learn more about the capabilities and actions of people when the unexpected arises and conditions are potentially extreme.
A task group was set up within the OECD/NEA's Working Group for Human and Organizational Factors (WGHOF) in order to further the understanding of "Human Intervention and Performance in Extreme Conditions". The purpose of the SSM research project was to supplement the work within the WGHOF with areas that would not be covered as broadly. The project also had as an objective to supplement the IAEA's work on "Managing the Unexpected".

Objectives

SSM defined the following objectives for the research project:

- To gain a deeper understanding and provide a more complete illustration of:
  - how people function in extreme and complex situations
  - the support needed in these situations
  - how to prepare and train for unexpected situations
- To learn from pre-existing research and, in particular, experiences from extreme accident and incident situations in the nuclear power industry as well as in other safety-critical industries (aviation, offshore, etc.)

The objective of the Authority was that the project would provide a basis for determining whether established safety policies, procedures/instructions and training in the nuclear power industry need to be developed further.

The expected content and scope were the following:

- a survey of relevant existing research and, in particular, industry experiences
- an analysis of a selection of relevant events from many safety-critical industries.

Important aspects to consider included problem solving and decision making, in particular in the following cases: a lack of information, limited resources in terms of staffing, time-critical phases, and stressful and extreme situations. Such situations may also include factors such as:

- established procedures and instructions are difficult to follow or are not at all applicable
- error messages or problem patterns do not match previously known conditions or mental models
- the impact of uncertainty or the lack of understanding of the situation where it might be difficult for the persons involved to trust the reliability of presented indications.

Results

SSM has established that the research provides a thorough overview of the challenges of unexpected events to people and organisations and the difficulty of identifying ways to take action and counter threats that arise.

The report explores the destabilising and threatening aspects of unexpected events and organisations established management of prevention of the unexpected by attempting to broaden the predetermined arena and solutions within organisations.

Furthermore, the authors describe a sample of available techniques for improving human capability to cope with unexpected events. One way forward is to develop resilience characteristics which are a compound of endurance and flexibility. This approach would apply to both the design of organisations and to socio-technical systems.

The report also covers the challenges this new approach to safety and managing unexpected events would present to regulators.

Need for further research

There are several aspects in this research which could be explored further. It is likely that SSM will not procure further research immediately, but the Authority will determine the need for potential further research over the next few years.

Project information

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Content

Summary

This report provides an overview of relevant literature and research on the topic of "managing the unexpected". The report offers a deep understanding of the factors influencing the ways in which individuals and organisations recognise abnormal complex situations, how they react to those, what they would need to improve in their performance, and what they could do to prepare to cope with unexpected, often critical, events.

The literature review covered, among others, topics related to:

- problem-solving and decision making,
- monitoring, detection and anticipation of threats,
- collective sense making of situations,
- adaptation, creativity,
- reconfiguration of teams, roles and responsibilities
- group dynamics, group thinking,
- resilience.

In this report the "unexpected" is understood as a mismatch appearing between perceived reality and expectations, not immediately manageable through comprehension and/or action.

Individuals, groups and organisations are very good at building expectations about their own and others' behaviours, as well as about external events. These expectations are partially based on the experienced patterns and on models of the functioning of the world. To a certain extent expectations drive individual and social behaviour.

But sometimes expectations are proved false and individuals, groups and organisations are surprised by unexpected events. There are multiple reasons for something to be perceived unexpected. In a nutshell, it is possible to say that something can be perceived unexpected because, before it happened:

- it was not thought of; or
- it was thought of but it happens with a frequency different than expected (ignorance of when); or
- it was thought of but it happens with a magnitude different than expected; or
- it was thought of but the mechanisms leading to it were misunderstood (ignorance of why).

The occurrence of unexpected events increases the probability that decisions must be taken under time pressure and with a high level of uncertainty about both the reality of the situation and the effectiveness of potential actions to be taken.

To take appropriate decisions under such circumstances is a challenging task. In addition to the effect on decision making of well-known cognitive biases (e.g. confirm bias), heuristics (e.g. availability heuristic), feelings and emotions, other important aspects play a relevant role in the ability to handle unexpected situations. Work processes, roles, standard and emergency operating procedures and routines facilitate cooperation within teams on the basis of patterns of behaviours and regularities in the interactions between people. While this is clearly a positive aspect when things go as planned, they can hinder the ability of teams to react to surprises. Evidences show that the more people are trained to follow predefined normative patterns in anticipated situations, the more destabilized they may be when facing unexpected ones.

Facing surprises disrupts the current mental representation of the situation and calls for the reconstruction of a proper understanding of it as a precondition for regaining control through the performance of appropriate actions. Examples of this phenomenon can be found in the analysis of many incidents, accidents, crises and disasters. In this report the Mann Gulch fire and the USS Vincennes attack on Iran Air Flight 655 are reported as illustrative examples of how the lack of proper understanding of the situation led to disastrous consequences.

The report presents a series of practical guidelines that have been proposed to help people and organisations in managing the unexpected.

For what concerns people, two main classes of approaches exist. The first one aims at improving the intrinsic abilities of the people in handling uncertainty and unexpected situations. They range from generic training modules (e.g. leadership and creativity training, Crew Resource Management training) to more practical training based on simulations, tactical decision games, serious games etc. While the former have the advantage of addressing important non-technical skills, the latter are, at least partially, able to take into account the context in which people may find themselves during unexpected situations. The second approach for improving the handling of unexpected situations is based on the application of tools and techniques for supporting the processes of sense and decisions making. In the report methods to support reasoning based on cognitive models of decision-making are presented (e.g. OODA cycle, critical thinking). Methods as the “Crystal Ball”, the “Ritualised Dissent” are illustrated as examples of techniques for supporting people in making sense of uncertain situations and to decide on the best course of action. As part of this approach to support people's ability to cope with the unexpected, a set of specific IT based support tools exists. Tools like the “Situation awareness support tools”, “Cognitive maps”, “Decision Support Systems” have the advantage of being suited for collecting and displaying critical information, for implementing critical thinking, collective decision making and uncertainty removal. Tools for supporting sense making also exist (e.g. “Argumentative tools” or “Sensemaking support system”) but they are mainly fitted for situations in which time pressure is not a critical issue.

Practical guidelines directed to organisations' need for managing the unexpected are more difficult to draw, since they entail the problem of designing and managing organisations. Five alternative, as well as complementary, perspectives are presented in the report: High Reliability Organisations theory, Normal Accident Theory, Resilience Engineering approach, Emergency management, and Safety culture theories. These different perspectives point out desirable aspects organisations should possess and nurture for being (better) prepared for handling unexpected situations and uncertainties. HROs theorists stressed the need to be preoccupied with failures, reluctant to simplify interpretations, sensible to details, committed to resilience and respectful of expertise. Normal Accident Theory, starting from a more pessimistic position, suggests to design organisations as simple as possible and/or to downsize them to avoid the traps related to complexity. Resilience Engineering suggests to improve the ability of organisations to adjust their performance and to adapt to unexpected situations by developing flexibility, networks and auto-organisation. Emergency management postulates that the normal functioning of an organisation, or of an entire society, will be overwhelmed by events well identified in terms of their nature, but whose timing of occurrence is unknown. Thus, this approach is focused on the development of emergency and crisis plans which have to be regularly executed in trainings and drills. Finally, Safety culture theories discuss the importance of culture and of the informal aspects of organisations in managing the unexpected. Despite it is hard to assess and change cultures, the management of the unexpected should be explicitly addressed by organisations, and this would require the organisation to be aware and acknowledge that unexpected things happen. To cope with surprises, a supportive safety culture would stress the point that compliance to rules and procedures is not sufficient and that the process allowing adaptability should be distributed throughout the system.

The question of handling the unexpected poses further challenges for regulatory activities. When nuclear operators acknowledge the existence of uncertainty, vulnerabilities and of the possibility for something unexpected to happen, they will have to shift paradigm in their safety management approaches. In addition to the more traditional aspects as anticipation, reliability, or redundancy, this paradigm shift will have to include the management of features such as diversity, adaptability, flexibility, robustness which are deemed to be necessary for handling unexpected situation. This will entail a challenge for regulators in the nuclear industry since they will have to formalise, regulate and monitor those aspects. But, from the regulators perspective, to deal with those abstract intangible characteristics is hard and may be eventually less compatible with public and society expectations on the role of regulators in the nuclear industry.

1. Introduction

1.1. Background

In the aftermath of the Fukushima accident, most of the nuclear safety experts and organizations recognized that this accident was strongly highlighting the challenge of the unexpected. Initiatives to better understand how people can work and act under totally unexpected, extreme and abnormal conditions have been taken. Among others, the OECD/NEA Working Group for Human and Organizational Factors (WGHOF) initiated work on the issue under the heading "Human Intervention and Performance in Extreme Conditions". Under the aegis of the IAEA Operational Safety Section of the Division of Nuclear Installation Safety, an International Experts' Meeting (IEM) was also held in Vienna in June 2012 on the theme "Managing the Unexpected", and another one in May 2013 on "Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant".

The purpose of this SSM research project is to complete the work within WGHOF and IAEA with parts that may not be covered in depth.

1.2. Issue and goals

The safety of nuclear installations is essentially based on a deterministic approach complemented by a probabilistic lighting: the defence in depth principle. This principle describes how five successive lines of defence will prevent or mitigate any nuclear accident. All these lines of defence are based on the compliance of the plant and its operation with approved safety standards, based on the consideration of anticipated scenarios, regarded as plausible.

However, all anticipation efforts do no protect against unexpected events. TMI and Chernobyl accidents have highlighted the limitations of the anticipation of vagaries of internal origin. The Fukushima accident has highlighted the limitations of probabilistic modelling of environmental hazards. Low estimated probabilities do not protect against the actual occurrence of catastrophic events, exceeding all design assumptions. In both cases, the safety model is then literally submerged, while the resulting nuclear accident is unbearable for the society.
This led the European Council to request "stress tests", and national nuclear safety authorities to embark on a process of evaluation and "hardening" of the safety of nuclear facilities in the face of extreme, unpredictable situations. However, while the technical implications of such a project may stay in the range of available expertise, its implications in the field of Human and Organisational reliability cannot be immediately identified.

This is why efforts are still needed to clarify these questions. The objective of this SSM funded research project on "Man's ability to handle unexpected events", is to gain a deeper understanding of i) how people recognize abnormal situations as such, and act during extreme and complex situations; ii) what kind of support is needed during these situations; And iii) how to prepare and train for unexpected situations. The purpose is also to learn how people can or cannot cope with the unexpected, from available research and experiences from extreme accident and incident situations, in nuclear power as well as in other safety-critical industries (aviation, off-shore, etc.).

Finally, the goal is to provide a basis to determine whether established safety policies, procedures or instructions, and training in the nuclear power field needs to be developed further to handle situations in which, for example, established procedures and instructions are difficult to follow or are not applicable at all, error messages or problem patterns do not match previously known conditions or mental models, or the level of uncertainty or the lack of understanding of the situation make it difficult for the staff involved to believe in presented indications.

1.3. Methodology

The first phase of the research project consisted in a literature review of existing experience and relevant research on “managing the unexpected”. The field of knowledge covered by the review includes:

- problem-solving and decision making, especially when there is limited information, limited resources in terms of staffing, time-critical phases, stressful and extreme situations with shock and surprise.
- monitoring, detection and anticipation of threats,
- relationship between action and comprehension, symptomatic versus aetiological control strategies,
- "satisficing" comprehension strategies to allow decision and action despite the uncertainty of the situation,
- collective sense making of the situation,
- adaptation, creativity,
- reconfiguration of teams, roles and responsibilities according to the criticality of the situation,
- trust in the sources of information, group dynamics, group thinking, sharing and propagation of information,
- influence of ethnographic / corporate cultures (e.g. uncertainty avoidance, adherence to rules),
- resilience.

They were explored through the following channels:

- The literature on decision making under uncertainty;
- The literature on managing the unexpected;
- The literature on organisational reliability / resilience;
- The literature on industrial accidents (petrochemical, chemical, nuclear, offshore) and transportation accidents (aviation, rail);
- The literature on crisis management, including natural disasters (e.g. Katrina, Sandy) and post-accident crisis management;
- Internet forums like Emergency Responders Group on Linkedin;
- The literature on the prevention and response to terrorist attacks;
- The analyses produced by the main nuclear safety authorities and safety experts in developing a response to Fukushima, particularly about the role of human and organizational factors;
- The literature on High Reliability organizations;
- The literature on Resilience Engineering.

In the process of this review, we gradually evolve the initial questions to a more explicit statement of the issues associated with potential new directions in nuclear safety strategy to ensure the robustness of crisis responses to extreme events.

2. Concepts for the expected

2.1. The “expected”

Why is the “unexpected” so disruptive to human behaviour and human reliability? Simply because human behaviour is driven by “expectations”. Hence to understand the management of the unexpected, we must first understand the role of “expectations” in the normal course of actions.

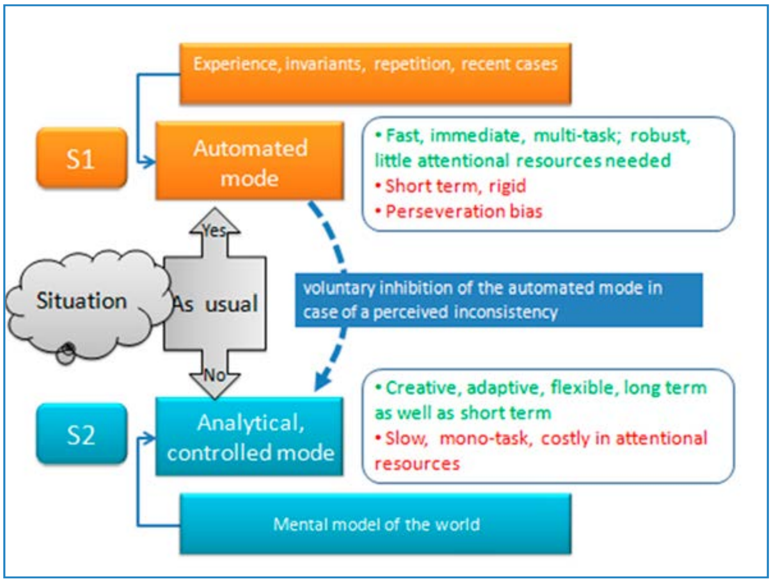
All natural cognitive systems are basically detectors of invariant patterns or recurrent features in their environment, filtering variations and adapting their detection and reaction strategies to what repeatedly impacts their condition. Human cognition developed this much further to include an ability to derive predictions of the future from recognized past regularities. Hence Human operators are dominantly anticipative cognitive systems. Both individual and social behaviour is driven by anticipations of the “world’s” behaviour. Perception itself is not a simple association between a stimulus and a response. The Gestalt approach to perception has been generalized by modern cognitive psychology to see conscious perception as both a ‘bottom-up’ and ‘top-down’ identification process, through which objects are recognized as a member of a predefined specific category (i.e. a bird), with associated features, properties, and potential functions. As Weick & Sutcliffe (2001) put it, *“Categories help people gain control of my world, predict what will happen, and plan my own actions”, and* “*Expectancies form the basis for virtually all deliberate actions because expectancies about how the world operates serve as implicit assumptions that guide behavioural choices*”. Hence knowledge from past experience directs perception towards relevant environmental stimuli, influences the course of information processing, and drives action choices. While trying to achieve their ends, operators use their experience to assess the whole situation, most often recognising it as ‘typical’, and then implement and monitor a typical action.

2.2. Levels of abstraction: the SRK model

Depending on the level of familiarity with the ongoing situation, this association of a situation to a corresponding response may be more or less automated or deliberate. In his SRK model, Rasmussen (1983, 1987) differentiates between three main behavioural control modes, or coupling modes to reality, which can be seen as three different levels of abstraction of the recognized regularities, generating correlated expectations about the world’s behaviour. At the *skill based* level, the expectation, which is not really conscious, is that the world is, and will react, exactly as usual, and the connection between situations and actions is then made directly at the detailed action level. At the *rule based* level, the connection is made at the level of operational principles, through the logical association between the situation and a combination of potential action responses. The potential actions to be performed are largely predetermined (e.g. procedural knowledge in long term memory, written procedures). Their practical implementation may still be achieved through a mental automatism, but the mapping between situations and responses needs conscious reasoning. Compared to the skill based one, it wins considerably flexibility through the combinatorial tree of "pre-packaged" actions. Finally, when the regularity of the situation is further reduced, this "combinatorial" flexibility can no longer deal with the faced irregularities: the connection mapping must be made at an even more abstract level[1], the *knowledge based* level, building on more generic properties (regularities) of the world, coded into the declarative knowledge of the operator.

2.3. A dual cognitive system

Recently, evidence has accumulated in favor of the idea that the cognitive processes supporting reasoning, decision, judgment, and social cognition, involve not one but two mental systems of (Evans and Over, 1996; Evans, 2003, 2008; Sloman1996; Stanovich 2004, Kahneman and Frederick, 2005; Kahneman 2011). "*System 1' reasoning is fast, automatic, and mostly unconscious; it relies on 'fast and frugal' heuristics offering seemingly effortless conclusions that are generally appropriate in most settings, but may be faulty, for instance in experimental situations devised to test the limits of human reasoning abilities. 'System 2' reasoning is slow, deliberative, and consciously controlled and effortful, but makes it possible to follow normative rules and to overcome the shortcomings of system 1*" (Evans and Over, 1996). In his recent book, *Thinking, Fast and Slow* (2011), the Economics Nobel Awards winner Daniel Kahneman also argues for two modes of thought: *System 1* is fast, automatic, frequent, emotional, stereotypic, subconscious; *System 2* is slow, effortful, infrequent, logical, calculating, conscious.



Depending on the problem, the context, and the person […] either system 1 or system 2 reasoning is more likely to be activated, with different consequences for people's ability to reach the normatively correct solution (Evans, 2006). The two systems can even compete: system 1 suggests an intuitively appealing response while system 2 tries to inhibit this response and to impose its own norm-guided one. What interests us here are the con-

[1] It is worth noticing that the same phenomenon can trigger behaviours at all three levels: a shining sun can make you put on sunglasses - skill based, encourage you to take light clothes in your suitcase - rule based, or help you to check your navigation with a sextant - knowledge based (and also influence your biological clock and metabolism, change your mood, or raise philosophical questions about a heliocentric versus geocentric world!). It is also worth noticing that skills can develop whatever the level of abstraction and complexity of the action itself: experienced mathematicians use many skills to lead their complex calculations.

sequences of this dual structure on how humans take experience into account (for example repetition), handle uncertainty, and react to the unexpected. Does the brain naturally compute statistical findings from observed experience, on the basis of which it would make choices following analytical rationality? The answer is rather “no”. Humans struggle to think statistically. In a variety of situations, they fail to “reasonably” associate probabilities to outcomes. The gaps between analytical rationality and actual decisions are usually called “cognitive biases”.

Different biases are associated with each type of thinking. Among others, Kahneman & Tversky (1973, 1979) have extensively researched the issue. They link these “biases” to “heuristics”, i.e. cognitive shortcuts allowing for adaptive benefits or cognitive resources savings:

- We actively seek out evidence that confirms our expectations and avoid evidence that disconfirms them (“confirmation bias”). This continuing search for confirming evidence actually stabilizes mental representations and decisions, but delays the realization that something unexpected is developing.
- We tend to overestimate the validity of expectations currently held ("pervasive optimistic bias"), which generates the illusion of substantial control2.
- We assess the probability of events by how easy it is to think of examples of such events (“availability heuristic”). Because memorizing is driven (filtered) by emotions (see below), the perceived magnitude of the consequences of something is reversely related to the ease to recall it: "if you think of it, it must be important". Hence the frequencies that events come to mind do not accurately reflect the probabilities of such events in real life, but the hierarchy of the memorized perception of the risk associated to them. This heuristic is very often beneficial.

Kahneman (2011) also states that humans fail to take into account complexity, and that their understanding of the world is based on a small and not necessarily representative sample of observations. They deal primarily with *Known Knowns* (things already observed). They rarely consider *Known Unknowns* (things that we know to be out there and relevant but about which we have no information). They forget the possibility of *Unknown Unknowns* (unknown phenomena of unknown importance). Finally, they have a much too linear and continuous vision of the world, hence wrongly assuming that future is predictable and will mirror the past, and minimizing the random dimension of evolutions.

2.4. The role of emotion

This notion of a dual mental system is supported by neurosciences. Recent findings suggest that the reasoning system has biologically evolved as an extension of the emotional system and is still interwoven with it, with emotion playing diverse and essential roles in the reasoning process. According to Damasio (2006), “Feelings are a powerful influence on reason...the brain systems required by the former are enmeshed in those needed by the latter...such specific systems are interwoven with those which regulate the body". And "Feelings are the sensors for the match or lack hereof between nature and circumstance...Feelings, along with the emotions they come from, are not a luxury. They serve

[2] This “bias” may build resilience: optimists are psychologically more stable, have stronger immune systems, and live longer on average than more realistic people. Optimism also protects from loss aversion: people's tendency to fear losses more than we value gains.

as internal guides, and they help us communicate to others signals that can also guide them. And feelings are neither intangible nor elusive. Contrary to traditional scientific opinion, feelings are just as cognitive as other percepts".

Of particular interest for our discussion is Damasio's idea that the contribution of the emotional system, far from being an archaic disruptor that would degrade the performance of the reasoning process, is an essential contributor to the global cognitive performance when it comes to manage uncertainty and complexity. "*Even if our reasoning strategies were perfectly tuned, it appears [from, say Tversky and Kahneman], they would not cope well with the uncertainty and complexity of personal and social problems. The fragile instruments of rationality need special assistance*". As an illustration, according to entrepreneurship research, expert entrepreneurs predominantly use experience based heuristics called effectuation (as opposed to using causality and analytical rationality) to overcome uncertainty.

In Damasio's theory, this assistance is provided by emotions through "somatic markers", which "*mark* certain aspects of a situation, or certain outcomes of possible outcomes" below the radar of our awareness. "Somatic markers are special instances of feelings [that] have been connected, by learning, to predicted future outcomes of certain scenarios. When a negative somatic marker is juxtaposed to a particular future outcome the combination functions as an alarm bell. When a positive somatic marker is juxtaposed instead, it becomes a beacon of incentive". Consequently, emotions provide instant risk assessment and selection criteria (pleasure / pain) that enable decision and action, particularly in the presence of uncertainty. "Emotion may increase the saliency of a premise and, in so doing, bias the conclusion in favor of the premise. Emotion also assists with the process of holding in mind the multiple facts that must be considered in order to reach a decision". "When emotion is entirely left out of the reasoning picture, as happens in certain neurological conditions, reason turns out to be even more flawed than when emotion plays bad tricks on our decisions". And Damasio describes the example of a patient who has impaired emotion. It leaves the patient capable of driving on very dangerous ice but incapable of determining which date to make the next appointment to: "he was now walking us through a tiresome cost-benefit analysis, an endless outlining and fruitless comparison of options and possible consequences."

2.5. The cognitive trade-off

One critical feature of the above cognitive processes is that, the more abstract the "connection" level to reality, the higher the demand on cognitive computational resources. So the next question is: how does the cognitive system manages to match the situational demand and the available resources? What are the fundamental stability conditions of the coupling, through cognition and action[3], between an operator or a team of operators and their environment?

According to the work of Herbert Simon (1982), another Nobel award in Economics (1978) but also a psychologist, that this coupling is achieved through "bounded rationality". It means that Humans, including human operators, do not achieve and not even seek

[3] Action and comprehension are inseparable: we act through understanding and we understand by acting (e.g. the "response" of a patient to a therapy helps the doctor to build and strengthen his/her diagnosis). Research in the medical field has also shown that doctors tend to miss a diagnosis that would leave them unable to find a therapy.

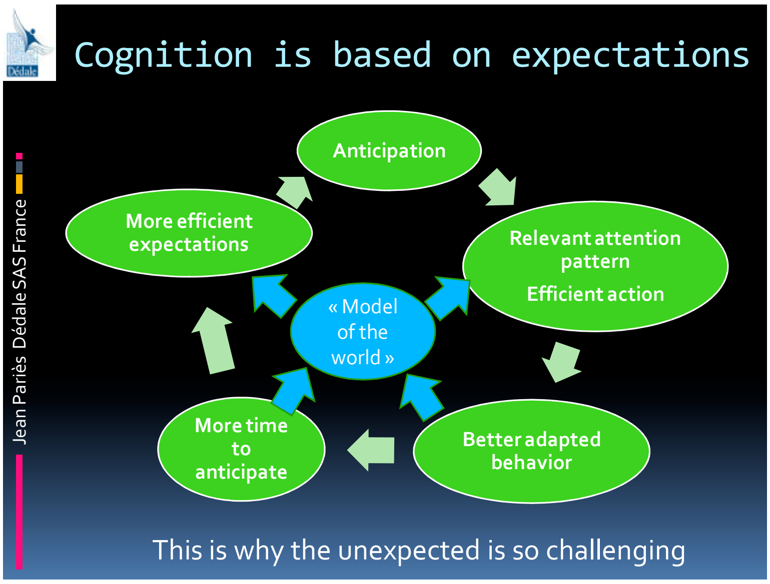
any “optimum” in either understanding or acting. They seek what is "**satisficing**" the achievement of their goal in the prevailing conditions. They "filter" reality and build a schematic mental representation of it, keeping only the information that is essential to understand “enough” and act “efficiently”. “*Every controller is a model of what it controls [system/environment]; Every good controller is a good model of what it controls*” (Woods, 2001). And they constantly adjust the "sufficiency" of their behaviour, hence the level of investment of their mental resources, by using heuristics rather than comprehensive analytical reasoning, adjusting trade-offs between, for example, the speed of execution and the accuracy of their action, or the thoroughness of their control and the efficiency of their action (thoroughness-efficiency trade-off; Hollnagel 2009).

In other words, human operators permanently manage a “cognitive trade-off” (Amalberti, 1996, 2001): in order to save their mental resources, they enter as little as possible into higher modes of coupling, while remaining sufficiently effective and reliable. In order to achieve this in a reliable way, they incorporate in their mental representation a model of themselves as controllers. They *"perceive" their ongoing level of control* over the situation and of their current and anticipated **margins of manoeuvre**. They feel[4] it when they understand enough, when they are doing well enough, in short when they "control" the situation and are likely to continue doing so in the foreseeable future. Otherwise (when feeling less control), they readjust efforts, increase their level of attention and/or reallocate it, try to save time, seek for help, try to simplify the task, change tactics or strategy or even higher level objectives. In short, they arrange for things to take a course as they can handle. This ongoing perception and prediction of control is at the heart of the concept of **confidence**. It is the correct setting of confidence that allows the efficient allocation of available mental resources to the relevant issues, and thus mainly determines performance. Much of the ability to control an everyday dynamic situation is not so much in knowledge and skills - always potentially insufficient - than in strategies, tactics, and anticipations that allow operators to ensure that the requirements of the situation are not going to extend beyond their expertise. The talent of "superior drivers" lies in their ability to control the complexity and dynamics of the situation itself, so they do not have to use their (superior) skills. However, ironically, this ability to minimize the need for superior skills implies to possess these superior skills.

In brief, anticipation is at the heart of expertise. As Woods (2001) puts it, “*Expertise is tuned to the future. Paradoxically, data is about the past; action is about the future. Prediction is uncertain and quickly spins out of bounds, yet anticipation is the hallmark of expertise*”. It is also important to understand that the effect of anticipations on cognitive control goes far beyond allowing an efficient use of the available mental computational resources. It generates a real **leverage effect** on the efficiency of the cognitive computing power, because the resources invested in building expectations are overcompensated by the savings they generate in real-time control actions, as we know exactly what to look for, what to do, what to monitor. And the better we know it, the more efficient the action, and the more time is available to build expectations. It is comparable to the rise of a **cognitive resonance** phenomenon, which gradually generates, by an ascending spiral, a dynamically stable state of the control process, in which the required computational power is minimal, This explains the time needed, even for an expert operator, to "get warm"

[4] This perception of control is of emotional nature; it is accompanied by a feeling of satisfaction or pleasure. Conversely, the perception of a loss of control would trigger the stress response, with the associated adrenalin. The pleasure of feeling in control is larger when the situation is inherently risky and difficult to control.

when starting an activity[5]. It also explains the feeling of “falling behind” which precedes a loss of control, when the resonance between anticipations and reality starts to break down.



A very important consequence of this leverage effect and its dynamic stability is that the cognitive control process is “robust yet fragile” (Carlson & Doyle, 2001): it can efficiently handle all kinds of disturbances within its adaption envelope, but may quickly enter a cascading stall if “surprised” by a disturbance outside the envelope.

	The dynamic stability of the cognitive control process can be metaphorically represented by a juggler. Once all the plates have gained momentum, the resources needed to maintain the movement are low, provided the juggler brings the right impulse at the right time. The process is robust: a trained juggler can move, turn, jump, throw up plates, and the like. But conversely, the process is brittle. As in any resonance, the phenomenon is very sensitive to mismatches. A wrong impulse at the wrong time, will quickly destabilize a plate, and recovery will require a sudden increase in control resources, with a rapid and accurate application of much stronger forces than the normal driving impulses. This call on resources can in turn upset the overall balance, absorb enough attention to compromise anticipation, divert enough attention from other plates to allow destabilization propagation. Very soon, if the initial recovery is not successful, the local destabilization spreads in a cascading demand of resources and a catastrophic collapse may ensue (Woods & Patterson, 2003).

[5] There is something similar in the start-up of a computer that requires the execution of functions (e.g. information transfer and processing), that need ... a running computer to be available. This start-up process has been called "bootstrapping", then “boot” process, by reference to a legend in which the hero jumps barriers pulling hard on the threading rings (bootstraps) of his boots.

2.6. Team work

The team is a basic unit of performance for most organizations and industrial work processes. Furthermore, in well-functioning teams, the interactions –the synergy- between team members enable levels of collective performance that go far beyond the mere addition of individual contributions. It is common to say that the whole is more than the sum of its parts. This collective dimension of performance introduces additional complexities in the role and impact of expectations. The individual interaction of actors with their work environment is complemented and modified by interactions with and between their colleagues. Effective teamwork is also promoted through appropriate operational frames within which tasks are to be conducted. These are provided by the company and can include the establishment of work processes, roles, tasks allocation, standard and emergency operating procedures, checklists, monitoring protocols, training, logistical support, and an integrated philosophy of operations. These structuring factors facilitate the emergence of regularities and patterns in behaviours and interactions, which are detected by the team members and transformed into behavioural expectations which deeply facilitate cooperation and reinforce the patterns. As an extreme example, these structuring elements of collective work enable airlines to roster crew members who may have never met each other before, let alone worked together, into a cockpit where they can quickly form an effective team.

However, while some of the components of a good team are built into the structure of the team, whether the team operates effectively also depends on other factors. These include team leadership, team cohesion, the way the team was formed, the way the team members relate to each other, the effectiveness with which information is exchanged, and the way people are treated, including being recognised and rewarded for their contribution to the team. High-performing teams have clear and shared values and goals, mutual trust and respect, well defined roles and responsibilities, effective communication, team members dedicated to the good of the team, and a leader who both supports and challenges his/her team members.

Group cohesion is a critical determinant of team effectiveness. Without cohesion, a team reverts to being a loose collection of individuals, acting according to their own objectives. In practical terms, cohesion is the combined effect of forces acting on members to remain in the group, such as shared culture (norms, values), interpersonal attraction (how much group members like each other), group pride (prestige attached to being in the group), task commitment (influenced by rewards associated with being in the group). A shared culture reinforces links within the group and acts as a basis for cohesion. People respond more patiently or sympathetically to people they like or who share a common way of thinking or acting.

There is a complex, circular relationship between group cohesion and predictability. Repetitive situations and stable behaviours allow the development of accurate mental representations of colleagues' behavioural patterns, competences, and weaknesses. These accurate representations generate predictability, which increase group cohesion: they simplify communication, facilitate empowerment and delegation (what people will be willing to delegate to each other, or accept from each other), as well as cooperation (what support people will provide colleagues with, and what call for assistance they will dare to ask from colleagues), and monitoring (mutual monitoring of colleagues' actions). Reversely, group cohesion and group culture increase predictability, because they increase the degree of conformity to "the way we do things here".

Cohesion is a necessary component for efficient crew teamwork and cooperation, but too much cohesion can become posing some threats to efficiency and safety in presence of the uncertain or the unexpected. When there is a very high degree of cohesion within a group, people tend to choose options that maintain unanimity and cohesion within the group, rather than express views that could provoke disagreements or conflicts. This phenomenon, known as 'groupthink' has explained a number of historical fiascos such as the decision processes leading to the failed 'Bay of Pigs' invasion during the Presidency of John F. Kennedy. It may compromise the detection of a wrong situation awareness, of an inappropriate decision, or of an exception to the expected routine, hence delay the realignment of the mental representation or/and increase the surprise factor. A remedy for monolithic thinking and excessive cohesion lies in the diversity of the membership. Reagans and Zuckerman's (2001) analyzed the data on the social networks, organizational tenure, and productivity of 224 corporate R&D teams. They show that pessimistic views about the performance of higher diversity teams (based on the hypothesis that decreased 'network density'—the average strength of the relationship among team members—lowers a team's capacity for coordination) are not confirmed by the data. They argue that teams that are characterized by high network heterogeneity enjoy an enhanced learning capability, and that both these network variables help account for team productivity.

A key underlying mechanism of team cohesion and non-formal team performance is mutual trust (Mayer, 1995; McAllister,1995; Kramer, 1999). Trust is a feeling and is difficult to define. It is a commitment to cooperate, based on anticipations, before there is any certainty about how the trustee will act (Coleman, 1990). Because certainty can rarely be acquired before acting and cooperating, trust can be considered as the foundation that enables people to work together (Hakanen & Soudunsaari, 2012). The feeling of trust is based on intuitions developed through past experiences and interactions. Trust is the assumption that regularities of the past will prevail over the variability (hence the uncertainties) of the present and the future. Trust is then a strategy to cope with the complexity of social interactions: familiarity absorbs uncertainty. Reversely, it allows for extending the possibilities of action, potentially increasing the complexity of the interactions. Trust usually takes a long time to develop and needs a series of positive experiences, and can be lost quickly through one single negative interaction. Trust does not imply sympathy: it is easy to think of people (colleagues, doctors, pilots...) we totally trust while we would hate to share a week-end with them.

Trust supports communication, and reversely open communication generates trust. Trust enables deeper interactions between team members, and deeper interactions generate trust. When people feel entrusted, they dare to express their views, feelings and perceptions, to share ideas, express and discuss differences and disagreements, and to accept healthy rivalries, which is the basis of innovation processes. A consequence of this is that trust increases the team's sensitivity to signals of abnormal developments in the situation, and enables flexibility in unexpected circumstances.

Sensemaking (see § 4.2) and decision-making (see § 4.3) are also inseparable from the social environment in which they take place: "[sensemaking] is a social process, influenced by "real or imagined presence of others." (Weick, 1995). "Decisions are made either in the presence of others or with the knowledge that they will have to be implemented or understood, or approved by others. The set of considerations called into relevance on any decision-making occasion has therefore to be one shared with others or acceptable to them" (Burns & Stalker, 1961). These authors contrast bureaucratic ("mechanistic") organizations and "organic" ones, in which "*Omniscience is no longer imputed to the head of the concern; knowledge about the technical or commercial nature of the here and now task may be located anywhere in the network; this location becoming the ad hoc center of control authority and communication. While organic systems are not hierarchic in the same sense as are mechanistic, they remain stratified. Positions are differentiated according to seniority (i.e., greater expertise). The lead in joint decisions is frequently taken by seniors, but it is an essential presumption of the organic system that the lead (i.e., 'authority') is taken by whoever shows himself most informed and capable (i.e., the 'best authority'). The location of authority is settled by consensus*". But even in very bureaucratic organizations, the determinants of individual conduct derive from perceived community of interest with the rest of the team, and not only from a relationship between individuals and the organization, represented by managers.

3. ... and concepts for the unexpected

"THINGS THAT HAVE NEVER HAPPENED BEFORE HAPPEN ALL THE TIME"
(SCOTT D. SAGAN - THE LIMITS OF SAFETY)

3.1. What is the "unexpected"?

The 'unexpected' is a mismatch appearing between perceived reality and expectations, not immediately manageable through comprehension and/or action. Such gap may be perceived for example because something happened differently (sooner, later, stronger, weaker, etc.) from what was expected, or because something else than expected happened, or because something happened while it was not expected, or because something expected did not happen. The continuing search for confirming evidence may delay the realization that something unexpected is developing. The recognition of such a defeat of expectations generates a "surprise". According to Weick & Sutcliffe (2001), surprise and the unexpected can take at least five forms:

- "Something appears for which you had no expectations, no prior model of the event, no hint that it was coming".
- "An issue is recognized but the direction of the expectation is wrong"
- "You know what will happen, when it will happen, and in what order, but you discover that your timing is off"
- "The expected duration of an event proves to be wrong"
- "A problem is expected but its amplitude is not"

Actually, according to the above definitions, many "unexpected" events happen to us every day. We expect someone, (s)he is late, or does not show up or someone else pops in, or simply, the telephone suddenly rings. But those are unexpected events that are rapidly understood, or deviations from expectations with no or negligible impact, or with obvious, immediate recovery or compensatory actions. In this document, what we are interested in are unexpected events which challenge the comprehension/reaction process, stop the normal course of action, and/or represents a threat to the system.

3.2. A typology of unexpected events/situations

More generally, a typology of unexpected events/situations could be built from many different perspectives, including:

- The subject or the origin of the unexpected: it could be the environment, other people's behaviour, a result, etc.
- The frequency (rather frequent, rare, remote, first of the kind) and the predictability of the unexpected (from well-known phenomena to unknown unknown);
- The disruptive potential (including the potential consequences) of the unexpected: negligible, serious, catastrophic;
- The resources available for (re)action: procedure, skills, time, assistance, data, team support, etc.

Among these dimensions, (un)predictability is a key issue, and refers to two fundamentally different cognitive situations. Studying the management of the unexpected by anaesthesiologists, Cuvelier & Al. (2010) report that according to practitioners '*there are different levels of unpredictability*', and some episodes are '*more or less predictable than others.*' They explain that '*Indeed, unexpectedness can arise in different ways. An unforeseen situation may be a situation that was already envisaged as possible by the anaesthesiologist before the intervention. In this case, the unexpected is not directly related to the* *event but to the time of occurrence of this event, that could not be determined with certainty by the practitioner before surgery. These situations are* potential *situations. At the opposite, a situation may be unexpected in its very nature: the event itself has not been foreseen by the anaesthesiologists. [...] These situations were* unthought-of situations *when they occurred.*' As pointed out by Wears& Webb (2011), this distinction can actually be referred to the fundamental discrimination introduced by Lanir (1986) between *situational* and *fundamental* types of surprise. Situational surprise is compatible with people's current model of the world and beliefs, and may possibly be averted by proper monitoring of relevant available signals, and foresight. Fundamental surprise defeats that model, and, unlike in the previous case, is literally created by advance information, as there is no relevant monitoring scheme available.

Westrum (2011) found that there are basically three aspects to threats: the predictability of the threat; the threat's potential to disrupt the system; the origin of the threat (internal vs. external). With these basic aspects, he derived a typology of situations including three main categories of threats: Regular Threats, Irregular Threats, and Unexampled Events.

- Regular threats are those that occur often enough to allow the development of a standard response (e.g. anticipated failures or operator errors). Trouble comes in one of a number of standard configurations, for which an algorithm of response can be formulated.
- Irregular Threats are more challenging, because it is virtually impossible to provide a response algorithm, as there are so many similar low-probability but devastating events that might take place; and one cannot prepare for all of them. Among those, the most challenging are the one-off events (e.g. Apollo 13 accident). Response implies improvisation.
- Unexampled Events are so awesome or so unexpected that it may appear impossible that something like this could happen. They require more than the improvisation of irregular threats. They push the responders outside their collective experience envelope, require a shift in mental framework, and basic abilities of the organization to self-organize, make sense of the situation and create a series of responses. The 9/11 bombing of the World Trade Center is a prime example of such an event.

Similarly, Paries (2012) suggests a taxonomy of threats based on the nature of the underlying uncertainty or ignorance:

- Ignorance of when (chronological ignorance): the phenomenon is known and (at least partially) understood in its mechanisms, but it is impossible to forecast precisely when it will occur (due to the complexity and non-linearity of the phenomenon, or due to the lack of data); there is usually an inverse exponential relationship between the frequency and the magnitude of the phenomenon. (ex: earthquakes; tsunamis);
- Ignorance of why (logical ignorance): the phenomenon is known, but no model is available to explain it and predict it (e.g. unexplained diseases), or no connection is made between that phenomenon and available models (because the signals are too weak, or because of a diagnostic error, or mental a representation error). It can also be that the phenomenon has simply no identifiable cause: this is exactly the case for 'emergent' phenomena.
- Ignorance of what (phenomenological ignorance): the phenomenon is not yet part of our model of the world (e.g. mad cow disease; 9/11 terrorist attacks).

3.3. Surprise and disruption

The disruptive potential of an unexpected event depends on several features, including its development and pervasion speed, the time-criticality and irreversibility of decisions to be made, and the criticality of its potential consequences. These features are usually embedded into the notion of 'emergency'. However, it would be wrong to equate the disruptive potential and the level of emergency. In 2005, NASA issued a report on the challenges of emergency and abnormal situations in aviation. Quote: 'some situations may be so dire and time-critical or may unfold so quickly' that pilots must focus all of their efforts on the basics of aviation—flying and landing the airplane—with little time to consult emergency checklists'. The report indicated that, although pilots are trained for emergency and abnormal situations, 'it is not possible to train for all possible contingencies'. More interestingly, the NASA report noted that a review of voluntary reports filed on the Aviation Safety Reporting System (ASRS) indicated that over 86 percent of 'textbook emergencies' (those emergencies for which a checklist exists) were handled well by flight crews, while only about 7 percent of non-textbook emergencies were handled well by flight crews. In other words, the disruptive potential of the 'unexpected' is much more depending on the absence of anticipation than on the objective severity of the corresponding threat.

3.4. Uncertainty and complexity

There is a close relationship between the unexpected, and uncertainty. The greater the uncertainty in a situation, the greater the chances for unexpected events to happen.

In physics and engineering, the uncertainty or margin of error of a measurement is a range of values likely to enclose the true value. In cognitive psychology and decision theory, uncertainty is defined as a state of limited knowledge where it is impossible to exactly describe a past event, or an existing situation, or a future outcome, or to predict which one of several possible outcomes will occur. As Lindley (2006) puts it: '*There are some things that you know to be true, and others that you know to be false; yet, despite this extensive knowledge that you have, there remain many things whose truth or falsity is not known to you. We say that you are uncertain about them. You are uncertain, to varying degrees, about everything in the future; much of the past is hidden from you; and there is a lot of the present about which you do not have full information. Uncertainty is everywhere and you cannot escape from it*'. The sources of uncertainty are numerous: limitation of knowledge, lack or excess of information, discrepant data, limitations in measurement and perception, errors in measurement and perception, semantic ambiguity, and the like.

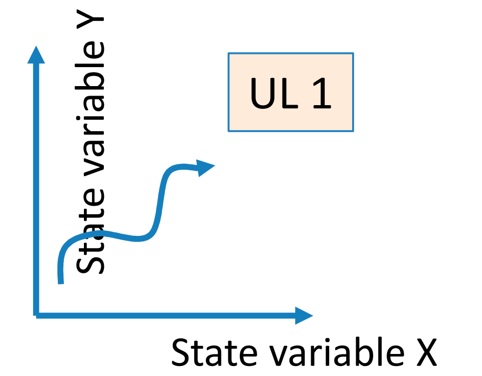
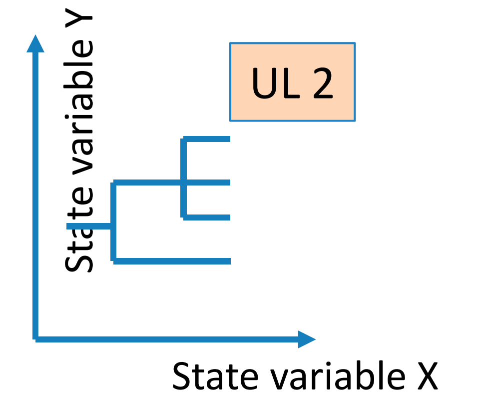
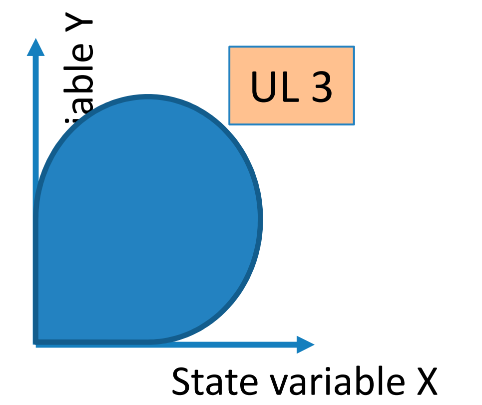
Uncertainty is sometimes differentiated from ambiguity, described as 'second order uncertainty' (Smithson,1989), where there is uncertainty even about the definitions of uncertain states or outcomes. The difference is that this kind of uncertainty is located within the human definitions and concepts, rather than an objective fact of nature. Similarly, the reference to uncertainty in risk management has also recently witnessed a clarification of the difference between *stochastic* uncertainty and *epistemic* uncertainty (Hoffman & Hammonds, 1994). Stochastic (or random) uncertainty arises from the intrinsic variability of processes, such as the size distribution of a population or the fluctuations of rain fall with time. Epistemic uncertainty arises from the incomplete /imprecise nature of available information and/or human knowledge. And this knowledge may be obtainable, or not. When uncertainty results from of a lack of obtainable knowledge, it can be reduced with gaining more knowledge, for example through learning, data base review, research, further analysis or experimentation. But uncertainty can also result from a more fundamental limitation of potential knowledge. Such limitation may apply to observation, even in 'hard sciences': In quantum mechanics, the Heisenberg Uncertainty Principle states that an observer cannot know both the position and velocity of a particle. It can also apply to the understanding process itself. The dominant scientific explanation mechanism currently available is reductionism, which consists of decomposing phenomena, systems and matters into interacting parts, explaining properties at one level from laws describing the interaction of component properties at a lower level of organisation. But an obvious question immediately arises: can we 'explain' all the properties of the world (physical, biological, psychological, social,…) through such a reduction process? It could be that we could *in principle*. The famous French mathematician and astronomer Pierre Laplace (1814) nicely captured this vision: *"We may regard the present state of the universe as the effect of its past and the cause of its future. A mind which at any given moment knew all of the forces that animate nature and the mutual positions of the beings that compose it, if this mind were vast enough to submit the data to analysis, could condense into a single formula the movement of the greatest bodies of the universe and that of the lightest atom; for such a mind nothing could be uncertain and the future just like the past would be present before its eyes."* The contention here is that the states of a macro system are completely fixed once the laws and the initial / boundary conditions are specified at the microscopic level, whether or not we limited humans can actually predict these states through computation. This is one form of possible relationship between micro and macro phenomena, in which the causal dynamics at one level are entirely determined by the causal dynamics at lower levels of organisation.

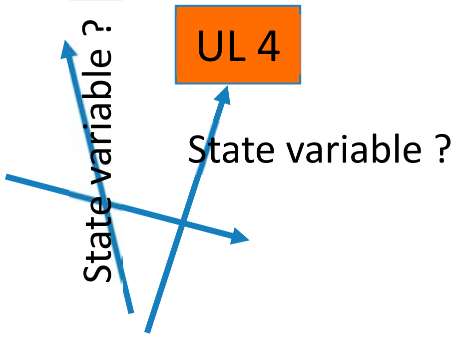
But the least one can say is that the reductionist strategy does not have the same usefulness for all aspects of the world. Life, but also societies, economies, ecosystems, organisations, consciousness, have properties that cannot be deducted from their components properties, and have a rather high degree of autonomy from their parts. About 80% of the weight (the cells) of my body die and are replaced every year, but I am still 'myself'. This broader form of relationship between micro and macro levels, in which properties at a higher level are both dependent on, and autonomous from, underlying processes at lower levels, is covered by the notion of *emergence*. Emergence is what occurs when simple components or systems show, through their interactions and evolution, a kind of properties or behaviour that is impossible to predict or explain by the analysis of these components or systems alone: No atoms of my body are living, yet I am living.

So there is a strong relationship between emergence and complexity. Complex systems are systems that exhibit emergent properties. This usually goes with some form of unpredictability, related to divergent and turbulent evolutions, and with some limitation of our comprehension capacity of this kind of phenomena, related to the fact that classical linear causality loses its meaning with such systems, because they include interlaced feedback and feed-forward loops. The notion of 'culture' provides a nice example of that: Culture is indeed both a set of values, beliefs, norms, representations, attitudes, postures, that frame the behaviour of a population, and at the same time the (re)cognition by this same population of established behaviours, that is to say, "the way we are doing things here". Hence the causality between values and behaviours is circular: values in the minds induce and stabilize patterns of behaviours in the real world, but these patterns of behaviours generate in the minds the corresponding representations and values (repetition becomes habits, habits become norms).

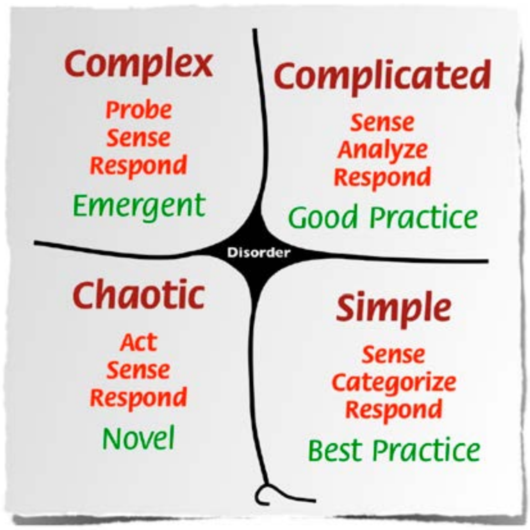
3.5. Typologies of contexts and ontologies

In artificial intelligence, and information science, ‘ontologies’ are the structural frameworks used for organizing information and for reasoning: an ontology formally represents knowledge as a set of concepts within a domain, and the relationships between those concepts. They provide a shared semantic structure to a domain, as perceived by its actors, and can serve as basis for the construction of formal reasoning or methods, to support the design of organizations and IT tools. Ontologies offer interesting opportunities to categorize uncertainty and complexity according to the challenge posed to decision making and risk management. Several attempts have been made along these lines in the business and strategic decision domain. Courtney & al. (1997) differentiate between four residual uncertainty levels (UL):

	• Level 1: Quasi deterministic: only one future, with uncertainty on variants that do not change the strategy
	• Level 2: A limited number of well identified possible future scenarios, each of them having a probability difficult to assess; best strategy depends on which one will actually occur
	• Level 3: A continuous set of potential futures, defined by a limited number of key variables, but large intervals of uncertainty, no natural scenario; as for 2, the best strategy would change if the result was predictable

	• Level 4: Total ambiguity: the future environment is impossible to forecast; no means to identify the set of possible events, even less to identify specific scenarios within this set. May be impossible to identify the relevant variables to define future.

Similarly, the ‘Cynefin framework’ (Snowden, 2005) also provides a typology of contexts based on the level of complexity of the situations and problems that may be encountered. That framework intends to provide guidance about what sort of explanations, decisions or policies might apply (Snowden & Boone, 2007). It defines five “ontologies”, in other words five different types of worlds, considering their properties and level of complexity:



The various domains of the Cynefin model.

Simple/Known: the relationship between cause and effect is linear and obvious, the strategy is *Sense - Categorise - Respond* and it aims at *best* practices.
Complicated/Knowable: the relationship between cause and effect requires expert knowledge and analysis, the strategy is *Sense - Analyze - Respond* and it aims at *good* practices.
Complex: the relationship between cause and effect can only be seen with the benefit of hindsight, the strategy is *Probe - Sense - Respond* and we can observe *emergent* practices.
Chaotic[6]: there is no understandable relationship between cause and effect, the strategy is *Act - Sense - Respond* and we can discover *novel* practice. The boundary between simple and chaotic is a catastrophic one (complacency leads to failure).

[6] The use of the word “chaotic” in this taxonomy refers to the common definition of a total disorganisation. It does not correspond to the meaning of the word “chaos” in the so called Chaos Theory, a branch of mathematics and complexity sciences, in which a chaos is the behaviour of a deterministic dynamic system highly

Disorder: we don't even know what type of causality exists, and people will revert to their own comfort zone in making a decision.

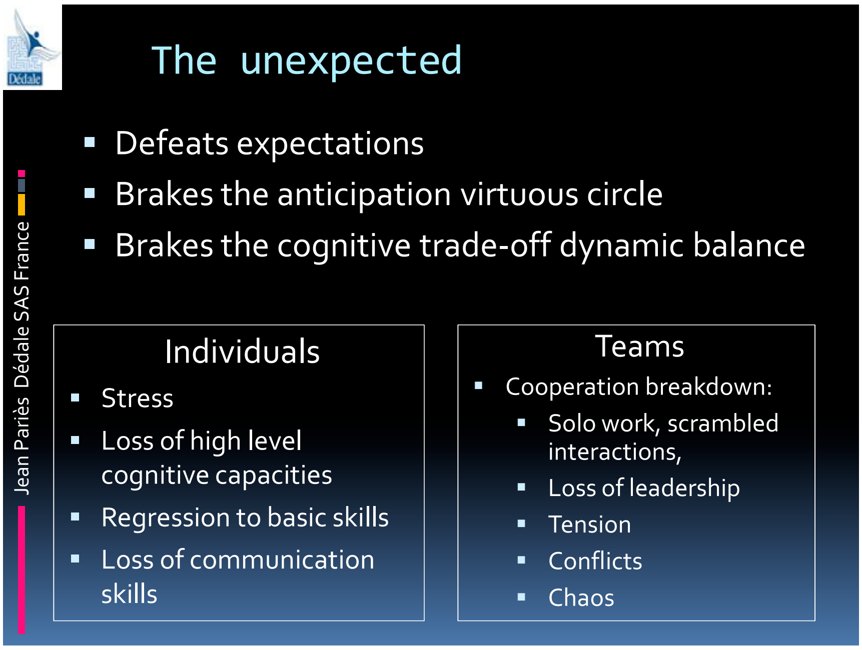
A third classification based on the validity domain of statistical methodologies is suggested by Nassim Taleb (2008):

Probability structures	Decisions	Simple (binary) decisions	Complex decisions
		A statement is "true" or "false" with some confidence interval ; Very true or very false does not matter; Decisions only depend on probability of events, and not their magnitude.	Both the frequency and the impact matter, or, even more complex, some function of the impact ; So there is another layer of uncertainty .
Thin-tailed: *large exceptions occur but don't carry large consequences;* "random walk " randomness; Gaussian-Poisson distribution		*Statistics does wonders* *Extremely robust to black swan*	*Statistical methods work surprisingly well* *Quite robust to black swan*
Thick tailed: *exceptions occur and carry large consequences;* "random jump" randomness; "fractal" or Mandelbrotian distribution + unknown probabilistic structure or role of large events		*Some well known problem studied in the literature. Except of course that there are not many* *Quite robust to black swan*	*Black Swan domain* *Do not base your decisions on statistically based claims. Or, alternatively, try to move your exposure type to make it third-quadrant style ("clipping tails").* *Extreme fragility to black swan.*

In this document, we will now focus on rare or unknown dynamic situations/events, to be managed by a team under time constraint, not covered by a procedure, associated with high stakes (major risks, serious consequences), and demanding some comprehension to be recovered.

sensitive to its initial conditions. Such systems are deterministic (there is no random influence on their behaviour, their future is fully determined by their initial conditions), yet unpredictable on the long term, because tiny differences in these initial conditions generate widely diverging outcomes ("butterfly effect"). One of the fathers of chaos theory defined chaos as "when the present determines the future, but the approximate present does not approximately determine the future" (Lorenz, 1963). Weather is a good example of chaotic behaviour.

4. Reactions to the unexpected



4.1. The stress response

The first thing unexpected events do on operators is to trigger unpleasant feelings. As Weick (1993) put it, “Evidence shows that when something unexpected happens, this is an unpleasant experience. Part of managing the unexpected involves anticipating these feelings of unpleasantness and taking steps to minimize their impact”. Along the same lines, while interviewing anaesthesiologists about their recollection of unexpected situations, Cuvelier & Falzon (2011) report about “[...] the emotional content of narrated episodes: in half the cases, interviewed practitioners spontaneously evoke memories of ‘fear,’ ‘stress,’ ‘concern’ or ‘anguish’ ”.

As already mentioned, these unpleasant feelings are associated with the perception of a *loss of control*, which triggers a stress response. Indeed, unexpected events defeat the anticipations that permit a *leverage effect* on the efficiency of the cognitive computing power. Hence, they destabilize the dynamic equilibrium of the “cognitive trade-off”, that allows operators to ensure the requirements of the situation are not going to extend beyond their expertise. Once destabilized, this dynamic equilibrium may be quickly recovered through different mechanisms that will be described below, and constitute the core of the management of the unexpected. If not, cognitive control may be lost through a cascading process in which the development of the stress reaction undermines the capacity of response and the feeling of not being able to respond increases the stress reaction. The outcome is then the onset of a crisis.

The stress response is a very archaic inheritance in the development of species, which allows a forced and fast re-adaptation to face an emergency situation, in which the balance between the situational demand and the resources of the individual is suddenly broken. However, the stress response mainly generates an optimization of the physical capacities, and maximizes the chances of survival through concealment, escape or attack (“fight or flight”). This augmented physical response is generally not suited to the requirements of modern emergencies, which rather have a cognitive nature. In this regard, the stress response has rather negative, incapacitating effects.

These incapacitating effects have been widely described in the literature (e.g. Staal, 2004; Starcke and Brand, 2012), and will only be briefly summarized below:

- Simplification or ‘tunnel vision’ (Braunstein-Bercovitz & al. (2001); Dirkin (1983)): focus on the simple, manageable (comfortable) details, while ignoring the larger, more consequential but threatening issues.
- Decreased willingness to make decisions: decisions are postponed; fewer decisions are made, decisions made take longer, the number of options generated and examined is reduced (Baumann & al. 2001; Giora 1987);
- Decrease of selective attention: inability to discern task irrelevant information from task relevant information (Braunstein-Bercovitz, et al, 2001)
- Fixation, mental blockage: It becomes impossible to revert to previous states, and impossible to consider other solutions than the ongoing one.
- Perseveration: maintaining the current strategy despite evidence of its inadequacy (Bourgeon 2011); Going into circles: people become less and less aware that they are repeating the same mental sequence
- Decreased monitoring of the execution of plans
- Tendency to fly away, to escape problems: more irrelevant tasks, pauses, irrelevant chat.
- Increased confirmation bias: seeking what confirms one’s hypothesis, rejecting inconsistent evidence
- Instability: inability to stay on the topic and see it through to its conclusion; lots of jumping from one topic to another without resolution
- Agitation, hyperactivity, nervousness, precipitation into action
- Increased propensity for violations (Hartley & Al. 1994)
- Regression to earlier habits, earlier acquired skills (e.g. regression to the mother tongue in a multicultural environment) (Barthol and Ku, 1959; Zajonc, 1965)
- Loss of communication willingness and abilities (Driskell, et al, 1999)
- Loss of team perspective (Driskell &all, 1999), aggressiveness against colleagues, team members (involved in the problem or not) (Wofford and Daly, 1997)
- Tendency to abdicate decisional responsibility, to transfer it to others, especially if they are perceived to be in control. ‘I follow my leader’ syndrome becomes more acute. (Foushee, 1984; Foushee and Helmreich, 1988)

4.2. Sensemaking

Suddenly facing something unexpected generates an offset between the current mental representation of the situation, based on expectations, and the reality of the situation. Proper understanding is momentarily lost and some discontinuity appears in the course of action: ongoing activity is interrupted by apparent discrepancies in available cues. “Sensemaking” is the mental and social process that will then allow for the reconstruction of a proper understanding, and the continuation of action, and rationalize what people perceive and do through the retrospective development of plausible meanings (Weick, 1995). Hence sensemaking is a particularly important concept for the management of the unexpected: it is an activity seeking to explain an unexpected situation, while selecting a possible future.

According to Weick, it is a voluntary activity, subordinated to the action, and triggered by a discontinuity of the action, i.e. by a state of confusion which cannot be overcome by the use of easily accessible information. « *[Sensemaking is] the deliberate effort to understand events. It is typically triggered by unexpected changes or other surprises that make us doubt our prior understanding*" (Klein & al., 2007). It is a reconstruction of meaning in order to "restore order" and a possibility of action. The accuracy of this reconstructed meaning is far less important than its plausibility and consistency with the decisions.

Sensemaking generates or filters the data that must be interpreted, and simultaneously generates an interpretation frame to incorporate these data for a coherent and plausible explanation. "*Sensemaking is about the ways people generate what they interpret*". "*[It] is about the enlargement of small cues. It is a search for contexts within which small details fit together and make sense*" (Weick, 1995). Particularly, it seeks for a reinterpretation of historical facts. *Central to the development of plausible meanings is the bracketing of cues from the environment, and the interpretation of those cues based on salient frames. Sensemaking is thus about connecting cues and frames to create an account of what is going on* (Maitlis & Sonenshein, 2010). Sensemaking is the simultaneous search of an explanatory framework and of data fitting into this framework. *"[It] is the process of fitting data into a frame and fitting a frame around the data*" and "*[it is] a process of constructing data as well as meaning*" (Klein et al., 2007). In this data-frame theory of sensemaking (Klein et al., 2007), a frame is an explanatory structure that links its constituent entities to each other within a common logical perspective. There are several types of frames, depending on the chosen perspective:

- Historical frames: explain the sequence of events and their causal relationships;
- Mapping frames: define and where we are, providing distances and directions to several landmarks, and showing possible routes to destinations;
- Scenario (or script) frames: explain our role or tasks as a complement to others' role or tasks;
- Planning frames: describe a sequence of planned actions;

A sudden encounter with the unexpected introduces a mismatch between the current frame and perceived reality. The resulting state of confusion and discontinuity of the action may then trigger two main types of reactions: i) attempting to keep the ongoing frame, but seeking additional data or re-interpreting the existing ones; ii) attempting to change the frame, or to replace it.

A central aspect of sensemaking is that it is 'enacted'. Enactement or enaction is a concept developed by Francisco Varela and Humberto Maturana to mean that cognition is not the processing of symbolic data representing the real world by an autonomous processor (the brain), but the inseparable outcome of the interaction between a whole biological person (cognition is 'embodied') and its environment (cognition is 'situated') (Varela& al., 1993). It means that comprehension is inseparable from action abd emotion: when people try to sort out a problem, they take actions (or inactions) that simultaneously generate the cues that they will use for sensemaking and that affect the unfolding of the event itself: "*There is a delicate tradeoff between dangerous action which produces understanding and safe inaction which produces confusion*" (Weick, 1988). An important consequence of this is that people not only see what they expect, but what they can act upon: "*people see those events they feel they have the capacity to do something about*" (Weick 1988). As an interesting illustration of that, research on medical doctors' diagnosis has shown that doctors tend to filter illness symptoms and incorporate them into a diagnosis consistent with, and limited to, their capacity to provide the corresponding care.
Last but not least, sense-making is a *collective* process and is nearly impossible in the absence of social processes that lead to the enriched collective awareness that facilitates the

‘*construction, discovery, and correction of unexpected events capable of escalation’* (Weick & al., 1999).

4.3. Decision making

Beyond the recovery of appropriate comprehension through sense-making, a confrontation with the unexpected clearly raises the issue of *decision*. Indeed, uncertainties associated with unexpected events create opportunities for multiple and possibly conflicting interpretations as well as for several potential courses of action. And a decision is the choice of a future course of action, in the presence of several possibilities. Cognitive Dissonance Theory (Festinger, 1957) argues that individuals make decisions to resolve the psychological tensions caused by holding contradictory views of beliefs. The descriptions of Human decision making processes mainly belong to one of two families: normative models, and naturalistic models.

Normative decision models tend to describe what an ideal and “rational” decision process *should be*. They are usually derived from economic theory (and the concept of “rational consumer’ economical choice) and use an analytical, math-based approach to “calculate” an optimal decision, that maximizes or minimizes an explicit or measurable criterion, for example profit, risk, time, etc. Normative models usually call for an inventory of all possible solutions, a comparative assessment of each of them in terms of cost/ benefit or risk/efficiency ratio, a selection of the best ratio, the implementation of the selected solution, the monitoring of the outcome, and if need be, a revision of the plan. To reach the final decision, they suggest a systematic sequence of mental operations inspired by the Plan-Do-Check-Act cycle of Deming’s wheel. For example, the DECIDE model (Clarke, 1986) used in aviation pilot training suggests the following sequence: detect possible options (Detect), assess them (Estimate), choose one (Choice), determine the implementation conditions (Identify), implement the solution (Do) and then check it (Evaluate). Normative models have been developed in reaction to natural decision ‘biases’, and lead in theory to a more robust decision process inspired by analytical rationality and explicit reasoning. They lead to better decisions in clear cut situations, when time pressure is low. They are typically embedded in problem solving check-lists addressing anticipated anomalies. As they are rather artificial, if not counter-intuitive, they call for a specific training. In addition to that, they are far more time consuming than natural decision processes.

Naturalistic decision models (Lipshitz & Strauss (1996, 1997); Klein (1989, 1998); Cannon-Bowers & Bell (1997); Zsambok & Klein (1997)) have been developed in reaction to the inadequacy of normative models to real time decisions in most work situations, characterized by high dynamics, incomplete and ambiguous information, uncertainties, multiple and possibly conflicting objectives, and organisational time pressure. They tend to describe what Human decision *actually is* in different contexts, in order to recognize its strengths and to find ways to further reinforce them. Their focus is not so much on *comparing* options than on *generating* solutions. Naturalistic decision models are basically “recognition-primed” decision models: they state that the recognition of a problem almost simultaneously triggers a heuristic intuition of a solution, which is then checked through mental simulation, and implemented with close monitoring, if assessed as satisfactory. However, this intuition of a solution may not be so easy, particularly in unexpected and poorly understood situations. In this case decisions get closer to creativity, ‘productive problem solving’ or sense-making processes. Productive problem solving takes place in unusual or unknown situations or circumstances: available data are repeatedly rearranged and processed until a solution is found. The solution often appears suddenly as a ‘bright idea' emerging from a specific data pattern after several attempts to rearrange the data as a way of making sense of them. The particular moment at which the solution appears is called the *'insight'*. The capacity to generate insight is called "serendipity".

The following table summarizes a comparison between both models:

Normative decision-making is better when:http://www.cfcsc.dnd.ca/irc/nh/nh9798/ - n52	**Naturalistic decision-making is better when:**http://www.cfcsc.dnd.ca/irc/nh/nh9798/ - n53
Time is not an issue	Time is critical
Decision makers lack the experience needed for sound intuitive judgements	Decision-makers are experienced in the given situation
The choice is among several clearly defined and well understood options	There is a high degree of uncertainty, ambiguous or changing conditions
It is necessary to justify the decision to outsiders (e.g. hierarchy, justice) or resolve disagreements within a team over which course to adopt.	Priority is given to risk management efficiency over liability issues
An optimal or best outcome is needed	A satisfactory outcome, rather than the best possible solution, is sufficing

The occurrence of unexpected events not only increases the likelihood that a decision must be taken, it also increases the probability that this decision must be taken in the presence of time constraint, and of a high level of uncertainty about the reality of the situation and the effectiveness of potential actions to be taken. In such conditions, normative decision methods are rarely effective, because of the lack of time, and/or because of the high level of ambient uncertainty, which both make an objective comparison of several different solutions difficult or even impossible. Hence, improving decisions for the unexpected mainly rely on improving the "natural" decision process. Furthermore, Paries (2012) highlighted that the more people are trained to follow predefined normative patterns in anticipated situations, the more destabilized they will be when facing the unexpected.

On a different perspective, an important notion concerning decisions for the unexpected is the notion of 'sacrificing decision'. As already discussed, in daily activities, decisions are 'satisficing', i.e. neither 'optimum' or completely 'right' when analyzed with the benefit of hindsight. In the presence of 'fundamental surprise' and in crisis situations, the lack of time, knowledge and resources becomes overwhelming. 'Satisficing' decisions are then unachievable and need to be replaced by 'sacrificing' decisions. A sacrificing decision must be made when no practical solution can be found in a specific situation while respecting the current objectives and constraints. The only way out is then through climbing the means-ends hierarchy and changing the current trade-off between high level objectives and constraints, sacrificing one or more of these objectives to the benefit of one of them. Analyzing the US Airways Flight 1549 ditching in the Hudson River, Paries (2010) argues that this event provides several illustrations of sacrificing decisions. 'A first example was the decision to ditch in the Hudson River itself. Captain Sullenberger said in [one] interview: "*I quickly determined that we were at too low an altitude, at too slow a speed, and therefore we didn't have enough energy to return to La Guardia, because it's too far away and we headed away from it. After briefly considering the only other nearby airport which was Teterboro in New Jersey, I realized it's too far away …*". Post event simulations showed that considering its speed, distance and altitude, the aircraft had actually enough energy to glide back to La Guardia runways. But this is what we know after hours of data processing and simulations. There was nothing available to the crew to determine accurately and reliably whether or not they could make a runway. Their only reference was their experience, their airmanship, their feeling of the situation. *"... And the penalty for choosing wrongly, and attempting to make a runway I could not make might be catastrophic for all of us on the airplane plus people on the ground."* So there was an implacable trade-off here: either the Hudson, certainly bad but possibly not catastrophic, or surrounding airports, possibly happy ending, with minimum damage to the airplane, but definitely catastrophic in case of failure of the attempt. What we have here is a nice piece of risk management, through a 'sacrificing decision': minimizing the odds of a disaster by deliberately sacrificing the most ambitious, potentially happy ending – but intolerant – branch of the options tree, to set up a kind of bottom line class of damage, associated with a ditching.'

4.3.1. Risk assessment methods

It may seem strange and even paradoxical that risk assessment methods appear so late in a note on the management of the unexpected. There is a reason for this: the note is intended to focus on "Man's ability to *handle* the unexpected", while risk management methods focus on how to treat the unexpected as if it was expected. However, risk management methods obviously deserve consideration and discussion within this note. Their development was initiated in the 50's with the efforts made in the post-war period to better control reliability and contingencies within the domains of strategic nuclear forces, aerospace industry and nuclear electricity production. The unexpected, including technical failures and "human error", was the "enemy". Methods of systematic anticipation of hazards, failures and their effects (fault tree, FMEA), and methods of a posteriori analysis of unexpected events (root cause analysis, causal tree) were developed. And while it was quickly realized that human operators were difficult to incorporate into predictive models, the attempt to treat them similarly to technical equipment by assigning them a calculable reliability coefficient (THERP), has long been in vogue and continues today (HEART). In the 80's "soft" "Human Sciences" have been introduced in safety thinking to help better understanding the role of individuals, teams, organizations and cultures in accidents. But while the focus of interest slowly shifted from technical to human failures, then from front line operators to latent, organizational failures (Reason, 1997), the core of the "safety model" has remained the same: a "safe world" is supposed to be designed, organized, manufactured, operated, and maintained according to predetermined rules, derived from scientific knowledge and Cartesian rationality. The goal is to reduce uncertainty, through developing a comprehensive and a deterministic - and if not, at least probabilistic- model of the world. Uncertainty is then quantified, and analytical rationality is applied to demonstrate that the system is fully controllable under predetermined operating strategies (e.g. procedures). This quantification is obtained through the concept of *risk*: a combination (usually a multiplication) of the probability and the magnitude of the predictable damage. This concept and the correlated capacity to quantify uncertainty did allow a considerable development of risk management. They provided tools to make decisions based on analytical rationality about the unexpected "as if" it was expected.

However, risk quantification methods do more than facilitating decisions: unnoticed to decision makers, they make decisions themselves. Indeed, they postulate an equivalence relationship between all kinds of risks, a "distant elephant" (a remote catastrophe) weighting no more than a close mouse (a small probable discomfort). Furthermore, not all uncertainties are calculable, and there is an epistemological break between the probabilistic and non-probabilistic randomness. Risk quantification methods focus on anticipated contingencies, on calculable uncertainties, and crush the long term uncertainty into the exponential discount of the thin Gaussian distribution tail (Taleb 2007; Bouleau, 2012). Consequently, "unknown unknowns", "fundamental surprises" (Lanir, 1989) and "black swans" (Taleb, 2007) occasionally brush off the Cartesian rational construction. When the "extremely low probability" suddenly equals to 1, when the "defense in depth" lines are all submerged by the same wave, the kind of rationality embedded into the past risk management reasoning is suddenly visible and rejected by the population concerned by the materialisation of the risk.

4.4. Collective dimensions

Being confronted to the unexpected poses to teamwork a real and double challenge: the team cohesion is undermined, while the cohesion demand is greater.

The team cohesion is undermined by the unexpected because it has usually been generated within the framework of recurrent and expected situations. What we have seen in Section 2.6 is, in short, that most of the synergy between team members emerges from the recognition of the repetition of invariant situational and behavioural patterns, which allows the construction of mutual representations and mutual trust, and enable expectations that greatly facilitate and fluidize cooperation in usual situations, very much like repetition allows the acquisition of expert routines and skills at the individual level.

The occurrence of the unexpected may destabilize these mechanisms and threaten the cohesion of the team. The prevailing structure of the team, with its associated roles distribution and skills, as well as the organizational hierarchy and available procedural responses, may not be adapted to the needed response. The mutual trust, mainly acquired during normal operations and based on the mutual recognition of skills, may no longer be valid in exceptional circumstances. Low rank staff, usually reluctant to speak up, may even feel less authorized to express their concerns that something unexpected is coming (which they often see!). New goals, new constraints, new expectations, new channels of communication, new stakeholders may be brought into play, calling for a significant reorganization of the team. Differences of status, interests and commitment (e.g. between regular employees and interim employees or subcontractors) which only have a minor impact on cooperation in normal situations, because they are framed and controlled by the prevailing rules and protocols, may suddenly reveal considerable impact in exceptional circumstances. This was particularly exemplified during the first moments of the Fukushima accident, when the sub-contractors' staff involved in the maintenance operations left the scene, as they did not feel committed to continue any role in these exceptional circumstances.

The unexpected also means stress, and when addressing the effects of stress, we have seen they include a loss of willingness to communicate and a loss of communication abilities (Driskell & al, 1999), a loss of team perspective (Driskell & all,1999), the occurrence of aggressiveness against colleagues and team members (involved in the problem or not) (Wofford and Daly, 1997). Also mentioned was a tendency to abdicate personal decisional responsibility and to transfer it to others, especially if they are perceived to be in control. The 'I follow my leader' syndrome becomes more acute. (Foushee, 1984; Foushee and Helmreich, 1988). Unexpected events particularly stress leaders, who may be challenged to make faster decisions, under higher levels of uncertainty, with less time to think and consult team members, while the impact of even minor decisions may be huge. Front line managers may lose their credentials very quickly if they lose control of their emotions, or demonstrate they are losing their vision of what to do. This creates opportunities for “situational leaders” to step in, based on specific experience or understanding of similar situations. The critical role of middle managers in framing and enriching the interpretation of unexpected events must also be highlighted, as they are positioned between strategic visions and front line managers.

Unfortunately, while the team cohesion is weakened, the situation demand for cohesion is greater in unexpected situations. Indeed, the usual cooperation mechanisms, based on the usual procedures, role distribution, and organizational hierarchy, are likely not to be appropriate to the situation. Hence organic dimensions of the collective operation, in which the determinants of individual conduct derive from relationships between individuals and perceived community of interest with the rest of the team, are likely to take precedence over bureaucratic dimensions, in which individual conduct derive from a relationship between individuals and the organization, represented by managers. The lead is taken by whoever shows himself or herself most informed and capable to make sense of the situation and to propose a credible response, which frequently means seniors. Usually cohesive team members will be more likely to support each other and operate in unison in carrying out the necessary response actions. However, this may not be enough to prevent falling into somewhat chaotic reactions. The emergence of credible solutions and situation related leaders may trigger conflicts between supporters of diverging interpretations.

Consequently, it would be unreasonable to expect professional teams to gain relevant response capabilities to the unexpected either from their organized functioning, or from their natural cohesion earned over time through familiarity. There is a need for *specific* training, and a need to design the teams specifically to be able to react properly to the unexpected.

Most high reliability organizations provide their front line operators with emergency training and their managers with crisis management training. Is emergency training also training for the management of the unexpected? The answer depends on the philosophy of that training. In aviation, nuclear industry, chemical industry, oil industry, manufacturing industry, a vast majority of emergency training is based on anticipated contingencies and predefined responses. The goal of the training is then to improve the capacity of people to recognize the emergency situation among the anticipated ones, and properly implement the predetermined response. The overall strategy is to make the anticipated situations envelope as exhaustive as possible, through experience feedback and imagination. The irony of this strategy is that “*the competencies needed to cope with the unexpected « in real time » are those that are lost in a continuous effort to anticipate and respond to all potential threats at the system*” Paries (2012). Training for the unexpected implies training in really unexpected, surprising, destabilizing situations, in which operators must learn strategies and skills to quickly recognize a discontinuity in the course of events, make sense of it, redefine and share “sacrificing” objectives, reorganize themselves, redefine roles and responsibilities, and communicate efficiently. Section five will elaborate on this. It is worth noticing that one major obstacle to such training is the prevailing combination, when not confusion, between training and checking, which makes it virtually impossible to expose operators to dead-end situations and inescapable failures.

Concerning the "design" of the team, several issues can be considered, including:

- the hierarchical structure, the authority gradient and the degree of autonomy of team members
- the level of homogeneity vs heterogeneity of the team in terms of expertise, jobs differentiation, polyvalence vs specialization, age, gender, culture…
- the philosophy of procedures and the procedural compliance policy
- the level of knowledge about the system

The level of homogeneity vs heterogeneity of the team is an important issue for the management of the unexpected. Heterogeneity can have positive effects, provided it does not threaten the cohesion of the team. Different points of view are more likely to be expressed, and they will enrich the collection and reinterpretation of data. This multiplicity of perspectives is also likely to reduce the odds for tunnelling effects and typical cognitive biases such as availability bias and confirmation bias to take precedence. A diversity of experiences and interpretive frameworks is frequently mentioned in the literature as a source of increased creativity (Weick , 1979 ; Earley and Gibson , 2002). On the other hand, heterogeneity can be an obstacle to an effective management of the unexpected. Heterogeneous teams are more likely to lack cohesion, less likely to share the same objectives and values, hence more exposed to conflicts.

Studying rescuers at the start of an emergency intervention, Dugdale & al. (2006) argue that current research in crisis management research tends to overemphasise formal organisational modes and does not adequately support ground level teams. They argue that their observations show a clear need to focus research on ground level communication and local coordination activities and to develop flexible communication tools and flexible coordination structures, and that robustness, flexibility and self-organisation are key issues in designing emergency communication systems.

4.5. Loss of control and crises

In the following, we will call 'crisis[7]' an episode in which a team of operators actually loses control on the dynamic process (or the 'situation') they are supposed to manage, to such an extent that safety is critically challenged[8] (i.e. a door is opened for an accident). With this definition, a potential outcome of meeting the unexpected is the onset of a crisis, and a key issue is crisis management.

Control may then be lost through a cascading process, breaking the congruence between understanding and action: comprehension is no longer able to support action, and actions – as well as responses of the outside world to actions- no longer support comprehension. Time is missing to do what people understand they should do, and attempts to recover engulf all available cognitive resources, propagating the loss of control over other aspects of the situation. The anticipative mechanisms that underlie the efficiency of cognition are overwhelmed and play against efficiency. By analogy with financial crisis bubble bursts, a loss of control can be seen as a burst of the "cognitive speculative bubble".

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[7] In the safety domain, the most common meaning of the word "crisis" refers to the post-accident state of organizations, that is to say, to the efforts made by a company, an institution, or a whole country, to cope with the shock waves of an accident destabilizing the staff, the company, the "clients", the residents, or even the whole society. In contrast, we are mainly interested in this paper to pre-accidental situations, and we focus on operational teams, rather than the entire organization.

[8] A loss of control only leads to a crisis when it carries potentially "serious" , threatening consequences.

As for financial crises, there is a strong initial tendency to deny the loss of control, which worsens the situation, leading to a waste of time and to delaying the needed response, while recovery conditions generally include a strong and quick response. Human operators do not engage easily in a sense-making activity, which is resource intensive. Because they cannot afford to spend the resources to permanently take a step back and redirect their attention to uncollected or neglected evidence, they rather tend to deliberately choose a (single) interpretation of the surprising reality they may face, and focus on it. This first interpretation is based on previous experiences, and ad hoc explanations 'invented' for the circumstances in a kind of 'cognitive Do It Yourself'. It may look acceptable and act as a decoy for long enough to generate a large offset between the real situation and its ongoing representation. Indeed, once a choice is made, people are led to further neglect other relevant data, pay attention to irrelevant issues, build wrong anticipations, and so on. This may eventually destabilize the "cognitive trade-off" that allows operators to stay in control of the situation.

A loss of control is also something perceived as such, with associated emotions, and an awareness of the loss of control leading to stress reactions that may amplify the loss of control. The effects of the associated stress have already been presented: they generally lead to a decrease in the capacity of response to the situation, and the perception of this decline along with the awareness of the increasing demands of the situation just feeds additional stress.

At the collective level also, the natural effects of a loss of control are self-amplifiers, and the main risk is the loss of cooperation. The sense of urgency and the associated stress trigger a tendency to withdrawal, lack of communication, loss of solidarity, exacerbation of pre-existing mutual distrust and lack of confidence. Disorganized interactions and tensions may start to develop, and propagate into a generalized chaos if leadership is lost. Depending on the nature of the crisis, a loss of leadership by the official leader may be compensated by situational leadership taken by someone better adapted to the specific situation (e.g. someone who has already experienced a similar situation).

4.5.1. A categorization of crises

The discussion of cognitive control earlier in this document highlighted two dimensions of the situation: its complexity (relative to the available resources), and time pressure (urgency). A third dimension was the criticality of the potential consequences of the decisions to be made and the actions to be performed. Actually, this third dimension is common to all crises, so while it does discriminate crises from other situations, it does not allow to discriminate between crises, hence categorize them. Consequently, crises can simply be differentiated in two main categories: complexity, and urgency.

The complexity crisis

The complexity of a situation may increase unexpectedly due to its objective, intrinsic dynamics (e.g. a patient's clinical condition worsens because of 'natural complications' which are known but not controllable; the cooling status and the core reactor state are less and less understandable after a series of failures and instrument losses like in the Fukushima accident). It may also increase unexpectedly because the situation changes without anyone noticing, under the effect of something which has been initially missed or misunderstood (a patient's clinical condition gets progressively worse following an undetected medication error; a flight situation is less and less understood as a warning has been missed or misinterpreted like in the Helios air accident). Finally, the complexity may be related to “unknown unknowns” (a patient's clinical condition gradually worsens after an unknown interaction between drugs).

The urgency crisis
The level of urgency associated with a situation is related to the ratio between the actions demanded by the situation and the actions which are possible within the available time, altogether with a raise of the criticality of these actions. The level of urgency may increase unexpectedly due to a sudden or progressive increase of the workload (e.g. the implementation of the multiple complicated post-failure procedures on the QANTAS 32 flight after a non-contained engine failure). In this case the focus is on the number of actions to be performed (in a limited time). We can then speak of an *overload crisis*. It may also increase unexpectedly because of a contraction of the available time, with critical deadlines to be met (e.g. resuscitation process after a heart attack). In this case the focus is on the criticality of meeting the deadline. We can then speak of an *emergency crisis*.

These two categories of crises do not necessarily call for the same management framework. In brief, for complexity crises, the key issue is sense-making; for urgency crises, the key issue is efficiency. In the worst case, these two categories can combine, like in the Fukushima example.

4.5.2. Managing the crisis

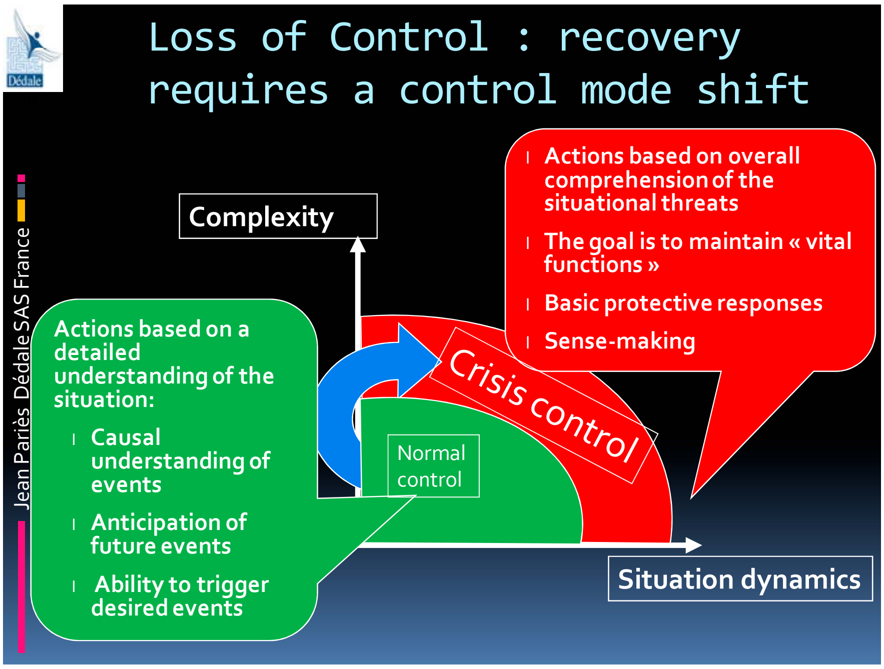
The hardest part of crisis management is probably not so much to get out of a crisis but rather to explicitly enter into it, which imply to recognize it! Both individually and collectively, it is psychologically difficult to recognize that we are losing control of the situation, and are in fact experiencing a crisis. This denial tendency is all the more detrimental that it delays the onset of recovery actions, while control recovery usually demands a fast and strong reaction.

Recognizing a crisis implies being able to detect and make sense of a number of warning signals which concern both the objective situation and feelings about the situation. Such signals include unexpected results (abnormal parameters, out of range variables), unexpected timing (things happen far too soon or too late), accumulation of abnormal facts, critical equipment failure, continuously increasing workload (with signs of fatigue, irritability, fed up, forgetfulness), loss of understanding, inability to make a decision, feeling of urgency, unease, “gut feeling”.

It is ‘natural’ to misuse these signals: as we have seen, mental representations are stable (and must be so to allow action), so we tend to maintain a feeling of control, of proper understanding, and find explanations to anomalies. We tend to think "it's probably that ..." or “it’s normal, it’s because...”. As Maitlis & Sonenshein (2010) put it, ‘*while research in psychology shows that such ‘positive illusions’ of control over the environment and of what the future holds can be highly adaptive (Taylor, 1989; Taylor and Brown, 1988), in certain contexts, such illusions are potentially lethal. [...] For example, Kayes (2004) notes how pre-summit assertions made by mountain climbers, such as ‘as long as the weather holds, we will have success’ and ‘we’ve got the Big E [Everest] all figured out’ prevented them from sensing what was really an ill-defined problem with no clear goal or solution, and ultimately led to the deaths of eight climbers’*. High Reliability Organizations theory on the contrary recommends that all actors be instilled with a “preoccupation with failure” and encouraged to use “vigilant wariness” at all times (Weick & Sutcliffe, 2001). As Maitlis & Sonenshein (2010) note it, '*Although optimism, and the hopeful situation assessments that often accompany it, is often intended to motivate team members before a dangerous mission, it can instead create blinkers and prevent individuals from adapting their understanding of an unfolding situation to accommodate new information as it becomes available*'. Adding to this blinkering effect, as already mentioned, "*people see those events they feel they have the capacity to do something about*" (Weick 1988). It is also 'natural' to misuse these signals collectively: we dare not say that we do not know, that we have a doubt, that we disagree, that we need help. We also assume that nobody else has a doubt. Weick (1990) identifies 'pluralistic ignorance', in which "I am puzzled by what is going on, but I assume that no one else is", as an important contributor to the early stages of a crisis. The countermeasure is to develop a culture in which everyone fearlessly expresses their potential concern about anomalies and/or saying "I don't understand". Collective sense-making in crisis is nearly impossible in the absence of social processes that lead to the enriched collective awareness that facilitates the '*construction, discovery, and correction of unexpected events capable of escalation'* (Weick et al., 1999). This concerns the premises of the crisis, the statement of the crisis, as well as the management of the crisis and the recovery of control.

Once the onset of a crisis is recognized, the next critical step is to make it 'official'. Anyone should feel allowed and encouraged to suggest that control is lost if appropriate. The leader should explicitly declare a crisis situation, using a dedicated phraseology.

Navigating the crisis
After recognizing a loss of control, the next challenge of a crisis is then to regain some form of control, and this requires a control mode shift:



This challenge takes different forms depending on the nature of the crisis (complexity or urgency). However, these differences are mainly concentrated on the relative importance of two basic and shared trade-offs. The first is the trade-off between action and the effort to understand. The second is the trade-off between implementation of known responses (plans, procedures, rules) and creativity.

The interaction between action and comprehension is well expressed by the notion of enacted sensemaking (Weick, 1988). As already discussed, '*the concept of enactment underpins the idea that people generate the environment through their actions and through their attempts to make sense of these actions*'. '*When people take action to try to sort out a crisis, they simultaneously generate the raw material that is used for sensemaking and affect the unfolding of the crisis itself* (Maitlis & Sonenshein 2010). *"Action clarifies what the problem may be, specific action renders many cues and options irrelevant, and action consolidates an otherwise unorganized set of environmental elements*" (Weick 1988). In other words, action is a mean to reduce uncertainty, to reduce the demand for more understanding.

However, this play on action versus comprehension is a risk management exercise: "*There is a delicate trade-off between dangerous action which produces understanding and safe inaction which produces confusion*" (Weick, 1988). Consequently, one can argue that providing people with the skills to efficiently manage this trade-off in order to maintain 'vital functions' at stake is perhaps the most powerful way to address crisis management.

As far as the compliant implementation/creativity trade-off is concerned, it is easy to find arguments that proclaim the victory of creativity, to the extent that by definition a crisis implies the defeat of the plans meant for controlling the situation. Yet things are not so simple. First of all, the cognitive performance losses caused by surprise and stress generally heavily affect creativity. Moreover, creativity can be dangerous in a complex situation where a part of reality is unknown or falsely known, and the consequences of potential actions can be widely misunderstood. But also the usefulness of pre-established plans and procedures may be greater and subtler in unforeseen situation that common sense suggests. Weick (1979) tells the story of lost soldiers in the Alps who eventually found their way trusting a map which afterwards turned out to be that of the Pyrenees. The history of aviation incidents also includes several examples of crews who have managed to land using the instrument approach map of the next airfield on the alphabetic list. This suggests that it may be more efficient to follow a wrong plan than nothing, because it prevents panic, keeps people moving and provides a frame in which they can update the sense they are making. However, committing to the wrong map can easily make your aircraft hit the nearest mountain. Preventing such catastrophic outcome implies at least two conditions. The first one is that the 'map' should be formulated at a sufficiently high level of the means-ends abstraction hierarchy: high level goals, principles, constraints, values (e.g. here are the North, the South, the general direction of the mountains, of the valleys, the maximum altitude passes, etc.). the second one is that the map is used with a relevant level of trust and doubt, avoiding extreme confidence and extreme caution, with people accurately knowing what they know and what they don't understand. This implies a permanent update of the collective interpretations based on the permanent collection and communication of new facts, and their discussion by the team in reference to the 'map'.

In summary, the following check-list developed within the framework of the above mentioned ICU research may provide a synthesis of a typical response to a crisis:

- Recognize and declare the crisis
- Identify it (complexity, urgency)
    - what has been lost, what are the main risks?
- Stabilize, regain some control
    - it cannot just be doing more and faster what was previously done;
- Redefine goals
    - refer to higher levels of the means-ends abstraction hierarchy,
    - envisage ‘sacrificing decisions’;
- Redefine and reallocate resources:
    - Leadership; delegation; redistribution of roles
    - additional resources: competences, equipment
    - usable procedures and protocols
- Clarify deadlines and adjust the pace accordingly,
- Properly close the crisis (not too soon, not too late; debrief within the team)

4.6. Resilience

Resilience has been defined as “the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions” (Hollnagel & all. 2006, 2011). This notion is therefore particularly relevant to think about the management of the unexpected, as we have seen that the unexpected is a major source of disturbance for our highly anticipative systems. There are two main ways to understand resilience. The first one is to think in terms of control, the second one is to think in terms of adaptation.

In the first perspective, socio-technical systems are regarded as (self)controlled systems, with a combination of open and closed control loops, with feedback and feedforward actions. Inspired by this model of controlled systems, we can describe a number of features that determine the resilience of a system. Hollnagel (2010) proposes a list of four “cornerstones” underlying resilience, with a view that is close to the robustness of its control function with respect to disturbances:

- The ability to react: the system must respond appropriately in real time (including to the unexpected). It must "know what to do", have a repertoire of responses and possess the necessary skills needed for their implementation, and more generally have the ability to create responses and adjust its operation. As these responses are closely dependent on the situation, it must have an ability to recognize the situation and select an appropriate response (decision). In correlation, it must have a supervisory capacity .
- The ability to monitor: the system must be able to know " what to watch " to detect potential threats, monitor its own internal state, the state of its processes, and its environment, in order to maintain the necessary regulations to fluctuations, and to detect destabilizations that require a change of functioning mode.

- The ability to anticipate: the system must have a sufficient phase advance , so to anticipate what will happen, predict the development of potential threats or opportunities, and more generally predict changes and their consequences , in order to maintain sufficient leeway to different time horizons.
- The ability to learn: the system must be able to expand its repertoire of responses based on its experience, but also to adapt its anticipatory strategies on the basis of the success or failure of past strategies.

Hollnagel has derived a “Resilience Assessment Grid (RAG) from these four abilities, which is reproduced in Appendix 1.

In the second perspective, organizations are regarded as complex adaptive systems. Since human actions dominate in socio-technical systems, the adaptability of the system is primarily a function of the actions of its social component, that is to say, individuals and groups operating in the system according to their objectives. The question is therefore how to preserve or develop the adaptive capacity in social systems. In the socio-ecological field, according to Scheffer & al. (2001) and Berkes & al. (2002), the existence of institutions and networks that learn and retain the knowledge and experience, and create flexibility in problem solving as well as a balance of power among interest groups, play an important role in the adaptive capacity and the avoidance of large-scale crises. Folke (2003) identified four critical factors that interact across spatial and temporal scales and that seem to be required to deal with the dynamics of natural resources during periods of change and reorganization:

- Learning to live with uncertainty. The existence of unpredictable surprises should be accepted as normal. Management should not seek to systematically eradicate disturbances, but rather to deal with their effects by spreading risk through diversification of both resource using modes and activities.
- Maintaining internal diversity to facilitate reorganization and renewal. In agriculture, many traditional groups maintain plant varieties with low yields as insurance against climate risks and diseases. These strategies include social investment in emergency crops and crops diversity as a strategy against tropical cyclones, and the growing of plants tolerant to disturbance.
- Combining several types of knowledge for learning. Combining different way of knowing and learning enables social actors to work together, even in an environment of uncertainty and limited information. Scientific understanding can be enriched by explorations of local and traditional knowledge. Social and ecological memory provides an accumulated experience of a continuous history of ecosystem management, includes lessons on how to respond to change, and nurtures diversity. It is a resource of creativity and adaptive capacity.
- Create opportunities for self-organization. Self-organization connects the previous three factors. It increases the capacity for interaction between diversity and disturbance. It nourishes the learning process, and roots it in a continuous process of brewing and trial and error of institutional arrangements and knowledge, enabling them to be tested and revised.

Moreover, the same characteristics that produce robustness under normal conditions (e.g. routines, procedures) can generate large weaknesses in presence of unexpected abnormal conditions. Conversely, the characteristics that produce robustness in exceptional conditions (e.g. diversity) can generate weaknesses in repetitive and anticipated conditions. The complex adaptive systems are generally "robust yet fragile " (under the terms of Csete & Doyle, 2002), and caught in a "spiral of complexity", a permanent race between the production complexity and complexity needs. A complex adaptive system is always partly "maladapted " to its environment, and its future adaptability results from this partial inadequacy. All complex adaptive systems strive to manage a balance between their degree of specialization and short-term optimization, and the robustness of their performance outside their adaptation envelope, that is to say, a compromise between optimality and fragility. The more is a system "fit" (optimized for a given equilibrium), the more sensitive it will be to disturbances that may disrupt this balance. Resilience engineering has to do with the proper management of this optimality – fragility trade-off, in other words, with the management of the adaptive capacity of a system, whether it is first-order adaptation (ability to maintain a balance) or second order (the ability to change and develop coping mechanisms to find a new balance).

Woods (2010) consequently describes the resilience of a system as being able to:
- Recognize the signs that its adaptability is falling or inadequate given the current level of uncertainty, of constraints and future bottlenecks;
- Recognize the threat of depletion of its reserves or buffers;
- Identify when it is necessary to change priorities in the management of trade-offs, and to the adopt a higher-order logic;
- Change perspective, contrast perspectives beyond nominal system states;
- Browse the interdependencies between roles, activities, levels, objectives;
- Recognize the need to learn new ways to adapt;
- Analyze its modes of adaptation and risk assessment;
- Maintain its ability to adapt, generate and constantly regenerate its potential to adapt to a spectrum of situations as broad as possible.Alpha

4.7. Organizational culture, safety culture

The term 'safety culture' has been coined in echo to the recognition that the formalized structures and processes of an organization are not able to fully determine the safety behaviour of its agents. The concept is particularly attractive for those who want to understand the management of the unexpected, since the unexpected exacerbates the role of informal dimensions of organizations. It was first introduced in 1986 in an International Atomic Energy Agency (IAEA) report into the Chernobyl accident to explain the organizational errors and operators' violations that led to the disaster (IAEA 1988). The IAEA then defined safety culture as the '*assembly of characteristics and attitudes in organizations and individuals which establish that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance'* (IAEA, 1991). Many industries around the world subsequently endorsed this concept as a goal-setting paradigm for preventing large-scale disasters associated with operators' behaviour. This has led to a proliferation of more or less consistent, more or less similar definitions. One of the most comprehensive was issued in 1993 by the UK Health and Safety Commission (HSC) which defined safety culture as '… *the product of individual and group values, attitudes, perceptions, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organization's health and safety management. Organizations with a positive safety culture are characterized by communications founded on mutual trust, by shared perceptions of the importance of safety, and by confidence in the efficacy of preventative measure.*' Safety culture is a facet of organizational or corporate culture, a concept used by management theorists to describe shared corporate values that affect and influence company members' attitudes and behaviours. According to Cooper (2000), '*the myriad of definitions of `organisational culture' and `safety culture' that abound in both the management and safety literature suggests that the concept of business-specific cultures is not clear-cut*' and '*due to a general lack of information on how* *culture works, or how it can be shaped, changed or otherwise managed in practice, there is no consistent definition of what corporate culture might be. The main difference between such definitions appear to reside in their focus on the way people think,* ***or*** *on the way people behave, although some focus on both the way people think and behave*'.

As a matter of fact, under an appearance of intuitive simplicity, the concept of (safety) culture is actually complex in the very sense of the term, that is to say, a recursive concept. Values in the minds induce and stabilize behaviours in the real world, and established behaviours generate in the minds the corresponding representations and values. 'Dominant logics shape daily routines, which in turn recreate structures, identities and expectations that enable and constrain certain collective practices' (Maitlis & Sonenshein 2010). Therefore, culture is a recursive enaction, a dynamic and very stable balance, and will maintain itself like a vortex in the river until the stream flows and the rock remains in place underneath. Any modification effort generates the emergence of spring forces back to the previous state. This poses many obstacles to safety culture 'improvement' programs, or alleged so. Nevertheless, let's assume it is possible to improve safety culture: what would a 'good' safety culture do for the management of the unexpected?

To answer this question, we need to look at what (a good) safety culture is supposed to be. Reviewing the organizational culture literature, Reason (1997) suggested that a (good) safety culture is a compound of:

- An informed culture (people seek safety information, both reactively - collecting data from near misses and accidents, and proactively - risk assessment, safety audits))
- A reporting culture (people feel involved in company safety management and honestly report their errors and mishaps)
- A just culture (people trust they won't be blamed for 'honest' errors)
- A flexible culture (facts and evidences contradicting the prevailing beliefs, strategies or policies are recognized and those are adapted accordingly)
- A learning culture (conclusions are drawn from the data collected and changes to procedures and equipment are implemented as necessary to enhance the safety performance of the organization

Ironically, the management of the unexpected is not an explicit dimension of that list, nor is it in most of the current definitions and descriptions of a safety culture. For sure, it could be argued that it is indirectly addressed. Indeed, a good, effective, or mature safety culture is assumed to reduce errors (hence the odds for unexpected events) and to improve the organizational sensitivity to abnormal facts (hence the reactivity to the unexpected) by fostering collective vigilance and organizational learning through open reporting and discussion of mishaps and system vulnerabilities. And a 'flexible culture' is also assumed to ensure proper responses to the unexpected and to a crisis. However, in the prevailing safety culture models and corresponding measurement techniques, a very normative culture, imbued with a 'total predetermination illusion' can be assessed as a good and mature safety culture.

Yet, as argued by Grote (2007), the management of uncertainties might be a key challenge for organizations and safety culture should then be reinterpreted as the expression of strategic choices made to handle uncertainties (minimizing uncertainties versus coping with uncertainties). Only a minority of the current visions of safety culture explicitly address the management of the unexpected in that sense. Borrowing from HROs' features and Westrum's notion of "requisite imagination", Hudson (2003) suggests that an 'informed culture" includes "wariness", meaning that at all levels of the organization people permanently look out for the unexpected. Weick (1987), also referring to HROs, argues that such organizations have a culture that encourages interpretation of rules, improvisation, excellence, as well as trust and openness between management and workers. These two perspectives clearly contribute the "good safety culture" model with two critical issues concerning the ability to handle the unexpected: the recognition that unexpected events will still happen whatever the efforts made to eradicate the unexpected, and the recognition that a mere compliance to rules and procedures cannot be sufficient to handle the unexpected.

But these two issues are left in the shadow by most current safety culture improvement approaches, and to say the least, their underlying safety model is ambiguous concerning the management of the unexpected. To put it simply, they express a hesitation between, and sometimes a compound of, two partially contradictory perspectives: a traditional compliance perspective and a HRO/resilience inspired perspective. In the former, the core strategy is the progressive eradication of the unexpected through the anticipation of all situations and the predetermination of relevant responses. Adaptability is centralized, feedback from experience is critical to inform and fine-tune the top-down control loop, and safety culture improvement efforts focus on adherence to procedures and reporting. In the latter, the unexpected is recognized to be inevitable and adaptability is distributed throughout the system. Safety culture improvement efforts focus on the sharing of values, priorities and interpretation rules that allow a coherent control of trade-offs at all levels of the organization.

Finally, it must be recognized that, to date, there is little direct quantitative empirical evidence confirming a positive correlation between a specific safety culture and safety performance.

5. Illustrative analysis of accident cases

The literature on the management of the unexpected includes several "case studies" illustrating the previous concepts and discussions. We have selected two of these illustrative cases and review them in the present section:

- Mann Gulch disaster (Firefighters)
- USS Vincennes attack on Iran Air Flight 655 (Navy)

The two accidents refer to situations where a team of operators had to face unexpected and threatening events. Data were collected mainly from investigations, witness statements, and accidents analysis reports and studies. From the comparative analysis of those accidents, a number of pitfalls have been identified that hinder efficient management of unexpected events by teams of operators. This should serve as a basis to improve current approaches for managing the unexpected. Particularly, emphasis was placed on how a breakdown in sensemaking can lead to disaster.

For each accident case, a summary of events is provided, and a detailed analysis is then carried out which seeks to highlight what did not work in each particular situation involving unexpected and threatening events.

A more recent case study of the successful ditching of a USAIR Airbus A320 can also be found in *Lessons from the Hudson* (Paries, 2011)

5.1. The Mann Gulch fire

5.1.1. Synopsis

On August 5, 1949, fifteen smoke jumpers parachuted into the Montana sky and onto a small fire near Mann Gulch. The crew leader, Wagner Dodge, was an experienced firefighter. With the unexpected winds, the fire blew up, cut off their escape route, and trapped the fifteen smoke jumpers and the one fire guard a scant hour and 45 minutes after they arrived. Only three came out alive, including foreman Dodge. Yet, Dodge had showed his men how to escape from the swiftly advancing fire. It took 450 men and five more days to get the Mann Gulch fire under control.

5.1.2. Analysis of the accident

Weick (1993) proposes an in-depth analysis of the Mann Gulch fire, suggesting the firefighting crew experienced increasing difficulties "making sense" of the events. The firefighters failed to understand the expected small fire had turned into a major blaze. When they landed at Mann Gulch that day, the crew was expecting an ordinary fire and was prepared for a routine mission. The optimistic vision of the situation led the fire-fighting crew to overlook early warning signals that the fire was more serious than expected. When they finally realized the danger, the situation was already out of control.

The Mann Gulch disaster illustrates how collapse of the group structure can impact the ability to make common sense of the on-going situation and provide a collective answer to it. The key aspects of the Mann Gulch disaster can be summarized as follows:

- Crew foreman Wagner Dodge was not familiar with the team. They knew each other through a three-week summer training, but had never actually worked together.

- At the time the crew jumped on the fire, it was classified as a Class C fire. So the crew expected to find a 10:00 fire (i.e. a fire that can be surrounded and under control by 10:00 the next morning). However, as the fire continued to grow and the flames looked more and more intense, the crew failed to realize how serious the fire was. They stuck to their initial perception of the fire until it was too late.

- The team was divided into two groups. Dodge and the fire guard had scouted ahead while the rest of the team was led by the second in command, William Hellman. Dodge found that the fire was worse than originally assessed from the air. He told Hellman to take the crew toward the river where he knew they would be safe from the fire. Hellman was more familiar with implementing orders and had no real authority on the men.

- Dodge and the fire guard ate a quick meal before they rejoined the others, unconsciously suggesting to the rest of the crew that the fire might not be as serious as it looked.

- When Dodge caught up with the rest of the team, he took back his position at the head of the line taking the crew toward the river. He became more and more alarmed but said nothing, widening the gap between him and the other crew members. From his position, Dodge was the only one that could see the fire had jumped the gulch just 200 yards ahead them and was moving toward them. He immediately turned the crew around with no further explanation. The crew got confused as Dodge's commands made no sense to them. At this point, only Dodge had a good understanding of the situation but he failed to share it with the rest of the team.

- Dodge had the crew angle up the 76% hill toward the ridge. They were quickly losing ground to the flames that were moving toward them at 610 feet per minute. As they were retreating, Dodge ordered the crew to drop their tools and equipment, started to set a small backfire and motioned for others to join and lie down in the area it had just burned. No one followed Dodge's instructions, and they all continue running with their tools for the top of the ridge. At this moment, Dodge ultimately lost the basis for legitimacy and the group completely disintegrated.

- Dodge survived by lying down in the ashes of his escape fire. Two other smoke jumpers also survived as they managed to find shelter into a small crevice. The rest (13 men) died for not following Dodge's lead.

In the Mann Gulch disaster, **group disintegration** played an essential role in the team's inability to make common sense of the situation they were facing. In the first place, foreman Dodge was not familiar with the team and stood apart from the others, creating a distance between him and the rest of the team. He did not share his impressions about the alarming fire which widened the space between firefighters and made them underestimating the intensity of the fire. When Dodge inexplicably turned them around, away from the river, the crew was left without explanations and got confused by the crew leader's instructions. Progressively, the entity of the crew dissolved as they were running away from the fire for the top of the ridge. When Dodge told his men to discard their heavy tools and equipment ("the very things that are their reason for being there in the first place"), the moment turns existential. Without their equipment, they are no longer firefighters, only endangered men "in a world where it is every man for himself" (Weick, 1993). The second in command William Hellman, who had no leadership skills, did not pass on Dodge's orders: the crew is left disorganized with no clear group structure. As the most experienced man, Dodge proposed a surprising solution at first sight: lighting a backfire to create a burned-over area that the fire would bypass, and lying down in the ashes. Given the circumstances (noise, heat) and the urgency of the situation (with the fire at this point less than 100 yards behind them and closing fast), Dodge had no time to explain further the rationale behind it and directed the team to join him onto the blackened ground. However, at this point the mutual ties between crew members have ceased to exist and each individual became "only solicitous on his own account" (Weick, 1993). Reactions then become more primitive and people tend to regress to their most habituated ways of responding. Instead of joining Dodge, the rest of the crew resorted to escape. The ferocious fire overtook the group as they continued to flee uphill, killing almost all of them.

Group disintegration - caused by weakened ties between members, poor communication and lack of recognized authority - is likely to have precipitated panic among crew members. Without those ties shared within a team (which imply mutual assistance, coordination, leader-follower relationship, complementary actions, and emotion sharing), the sense of danger increases. Individuals become isolated in the face of danger. Only blind obedience would have enabled to maintain ties between crew members and save their lives.

5.2. USS Vincennes attack on Iran Air Flight 655 (U.S. Navy)

5.2.1. Synopsis

On July 3, 1988, the USS Vincennes, a U.S. Navy warship, was cruising in the Persian Gulf. In the context of Iran-Iraq war, its presence was intended to escort and protect oil tankers that crossed the conflict area. The USS Vincennes was engaged in a battle with Iranian gunboats that had attacked U.S. forces earlier in the morning when an oncoming aircraft was detected on its radars. The course of the unknown aircraft was such that it was headed directly for the USS Vincennes. The U.S. warships began to issue increasingly urgent warnings on both military and international air distress frequencies, and tried several times to contact the non-identified aircraft. As there was no acknowledgement, the aircraft was declared "hostile" and Captain Rogers, the Commanding Officer of USS Vincennes ordered to fire two Standard surface-to-air missiles. The suspect aircraft was struck and blew up about 6 miles from the USS Vincennes. It turned out to be a commercial civilian airliner from Iran Air with 290 passengers and crew on board. There were no survivors, which makes Iran Air Flight 655 one of the deadliest accidents in aviation history.

5.2.2. Analysis of the events

July 3, 1988

Tensions were already high in the Persian Gulf. The headquarters had warned Captain Rogers, the Commanding Officer of USS Vincennes, there was likely to be significant Iranian forces' activity on that day.

6:30am The USS Vincennes was returning from an escort duty, passing through the Strait of Hormuz when Captain Rogers was informed that several Iranian gunboats were maneuvering around merchant vessels in the area. A helicopter was sent on a reconnaissance mission and was fired upon. The USS Vincennes decided to take military actions in response to the attack.

The USS Vincennes was on a peace support mission when it decided to engage the Iranian gunboats as a reaction to its reconnaissance helicopter being fired upon. Naval battles are rare. For many sailors aboard the USS Vincennes, this was their very first fight. The crew was no accustomed to wage such a surface battle. Workload aboard the USS Vincennes therefore significantly increased.

9h47am About 90km away, at Bandar Abbas airport, civilian airliner Iran Air Flight 655 (Airbus 300) took off 27 minutes late for a regular flight over the Persian Gulf to Dubai. Two minutes after IA655 took off from Bandar Abbas airport, the advanced tracking radar of the USS Vincennes detected the aircraft was coming its way. The Vincennes and most airliners were equipped with Identification of Friend or Foe (IFF) electronic boxes that allowed establishing identities. Being a commercial flight, IA655 transmitted a correct transponder code typical of a commercial civilian aircraft. Yet, the crew suspected it might be a decoy as they had been warned of a possible air attack for that day. A quick check of a listing of commercial flight schedules over the Persian Gulf missed the clear listing for Flight IA655. The command center was immediately warned of a potential threat approaching the ship.

Bandar Abbas airport is known to be used by both civilian and military aircraft. Particularly, it recently had become the center for Iran's force of F-14 fighter jets. While engaged with Iranian gunboats at the same time and warned of a potential air attack, the Vincennes mistakenly identified Flight IA655 as a possible Iranian Air Force F-14. The operators could not immediately match the non-identified aircraft to civilian flight IA655 because it was behind schedule due to its delayed take-off. The operators were also confused by the four different time zones in the Persian Gulf.
Due to the specific context on that day, an air attack was plausible which led the Vincennes' crew to favor the scenario of a military F-14 fighter jet. As a consequence, the approaching aircraft became suspicious as soon as it appeared on the Vincennes' radar screens, although it was flying on a designated commercial airway and transmitting a civilian IFF code.

9h49am The Vincennes attempted to contact IA655 and broadcast increasingly urgent messages to warn the approaching aircraft to change course. Warnings were issued on both civilian and military frequencies. However, they were addressed to a non-existent "Iranian F-14". There was no response.

Of the 10 warning messages sent by the USS Vincennes, 7 were broadcast on military frequency which could not be received by civilian Iran Air Flight 655. Three warnings were issued on civilian frequency. However, the idea of an attacking military fighter becoming more and more fixed in the minds, those messages were made specific and only addressed to an unidentified Iranian F-14. Hence, though Iran Air 655 heard the warnings, the pilots did not answer as messages referred to a military fighter jet which had nothing to do *with their Airbus 300 aircraft. Moreover, the pilots of IA655 were also busy communicating with Bandar Abbas and Dubai air traffic controllers at the same moment.*

9h50am The IFF signal code of the approaching aircraft seemed to change suddenly, briefly displaying those of an Iranian F-14. The operator immediately issued an alert, spreading more doubt in the Command Center. The Anti-Air Warfare Commander (AAWC) – who was in charge of the USS Vincennes' air defense - was granted authorization to shoot down the aircraft if approaching 20 nautical miles close to the ship.

Actually, the operator's mouse was still pointing at Bandar Abbas airport. The military IFF code that briefly appeared on the screen corresponded to an Iranian F-14 which was parked on the ground. The operator, convinced of an imminent attack, mistakenly assigned the military code to Iran Air Flight 655. More generally, it seemed that from the first contact, various personnel of the USS Vincennes began to report an "Enemy" IFF code associated with Iranian F-14s, although none of the data recorders reported any IFF response other than "Commercial". Due to the context, the crew was exclusively focused on a military attack, highlighting how confirmation bias can lead people to immerse themselves in a search for information that would support their position.

9:50am While the USS Vincennes was still engaged with Iranian gunboats on the surface, the front cannon of the USS Vincennes got blocked and Captain Rogers had to trigger an emergency U-turn so that the rear cannon could take over. During the maneuver, the warship tilted significantly which considerably disturbed the whole crew.

While dealing with the non-identified ("assumed enemy") aircraft, the Commanding officer still had to manage the surface battle with Iranian gunboats. The workload was significantly high aboard the USS Vincennes, and tension was at a peak.

9:51am In the Command Center, the lieutenant noticed that the approaching aircraft was actually transmitting a civilian IFT code again. He immediately informed Captain Rogers. However, the latter was still worried about the silence of the unknown aircraft, particularly because the US Intelligence had warned them about the possibility of attacks around July 4th, 1988, including potential suicide attacks. Further, the officers identified the flight profile of Iran Air Flight 655 as being similar to that of an Iranian F-14 during an attack run. Given the threatening flight profile and decreasing range, the aircraft was declared hostile.

Captain Rogers knew commercial airliners always answer. In the case of military aircraft, those who did not respond always end up diverting. The present situation did not correspond to any previous known model. Moreover, the approaching aircraft did not seem to use any radar to target the USS Vincennes. Yet, Captain Rogers had doubt in his mind. Stakes were high. As Commanding Officer of the USS Vincennes, he had a heavy obligation to protect his ship and his men.

9:52am The AAWC asked Captain Rogers for confirmation that the aircraft would be shot down at 20 Nm unless it changed course. Captain Rogers held fire, waiting for more information and still hoping that the aircraft would change its trajectory.

9:53am The aircraft was 13 nautical miles away from the Vincennes. While it was still on its assigned climb out airway, it started to drift slightly and was then flying 4 miles west of the usual commercial route. Tension was mounting aboard the USS Vincennes. Captain Rogers requested more information on the aircraft. After a few seconds only, the petty officer reported the suspect aircraft was descending toward the ship. The information was assessed reliable and passed on to the Commanding Officer.

Actually, the Airbus was ascending according to its usual flight plan, and not descending as claimed by the petty officer. This was later confirmed by analysis of recorded data. Poor display, huge amount of data, and time pressure surely have contributed to this misinterpretation. As the crew was getting more and more convinced of an attack, the (erroneous) indication of a descending unknown aircraft flying outside the prescribed commercial airway corroborated the scenario of an Iranian F-14. At this point, everything tended to support the scenario of an attack. Captain Rogers still had doubt and waited for more information that would contradict their current stand until the last moment. Yet, he never tried to challenge the data provided by his crew.

9:54am The aircraft was now 11 nautical miles away. Captain Rogers knew missiles have to be fired before the aircraft closes within its missile firing range of 10 miles. Decision must be made before this limit. The anti-air warfare commander recommended to fire. Everybody had in mind what happened to the USS Stark a year ago, when an Iraqi fighter bomber killed 37 sailors as the Captain of the USS Stark hesitated too long. Captain Rogers decided to authorize the firing. The USS Vincennes issued a final warning on military frequency.

The Commanding Officer waited until the last minute to authorize firing, under the pressure to act quickly. The crew feared the scenario of the USS Stark would repeat itself. The USS Stark was a U.S. warship that nearly sunk on May 17, 1987 following an Iraqi attack. The crew of the USS Stark hesitated and reacted too late to the attack of the Iraqi fighter bomber which fired two missiles that hit the U.S. warship. 37 American sailors were killed in the attack.
Ever since the USS Stark attack, vigilance have intensified in the Persian Gulf and U.S. forces have been less tolerant of such threats. As a result of the near-sinking of the Stark, rules of engagement have evolved to authorize positive protective measures in case of hostile intent: U.S. warships in the Persian Gulf did not have to wait for the enemy to take the first shot.
Captain Rogers knew his primary obligation as Commanding Officer is the protection of his own people. As the oncoming aircraft closed to its missile range limit of 10 miles, he considered the threat was too serious and decided to shoot down the aircraft to avoid another Stark disaster. Time pressure was at a peak and Captain Rogers had to make decision under very trying circumstances. Only 4 minutes elapsed from the time Captain Rogers was notified of a possible oncoming threat and the decision to fire the missiles. During this time, he was also dealing with the Iranian gunboats on surface.

9h54min43s The USS Vincennes launched two surface-to-air missiles which intercepted the Airbus 300 at an altitude of 13, 500 ft. Iran Air Flight 655 had been flying for less than seven minutes when it tumbled in flames into the Persian Gulf. There were no survivors.

The attack of USS Vincennes on Iran Air Flight 655 is an interesting case of a crew's inability to make sense of the situation. The different aspects of managing the unexpected can be summarized as follows:

- **Information available**
  The following table gathers information that was available to the crew and which tipped the scales in favor of each of the two possible scenarios: either this was a civilian aircraft or an enemy attack.

Information in favor of an enemy attack	Information in favor of a civilian aircraft
The aircraft briefly transmitted a transponder IFF code associated with Iranian F-14s (*). The aircraft did not respond to radio warnings. The aircraft took off at the same moment the USS Vincennes was attacked by Iranian gunboats. The aircraft schedule did not correspond to any regular commercial lines (*). The aircraft was heading toward the USS Vincennes, flying slightly outside the usual commercial air corridor. The aircraft was descending toward the USS Vincennes (*).	From the moment it appeared on the radar to the time it was shot down, the aircraft actually transmitted a transponder code typical of a commercial civilian aircraft. The approaching aircraft did not use any radar to target the USS Vincennes. The aircraft mostly flew within the prescribed commercial air corridor, even if it seemed to drift slightly just before decision was made to fire.

(*) *Information later proved to be wrong*

From the above table, the scenario of an enemy attack displays more arguments that those of a civilian aircraft. None of those pieces of information are sufficient to make a clear-cut decision. However, they add up to favor the enemy attack scenario. Three out of the six arguments associated with a possible attack were actually wrong. Yet, the crew of the USS Vincennes only questioned pieces of information associated with the civilian aircraft hypothesis:

- “The aircraft transmitted a transponder code typical of a commercial civilian aircraft”
- The crew suspected it was a decoy to hide its real identity.
- “The approaching aircraft did not use any radar to target the USS Vincennes”
- The crew suspected a suicide attack instead of a missile attack, as suggested by the US Intelligence earlier that day.
- “The aircraft mostly flew within the prescribed commercial air corridor, even if it seemed to drift slightly just before decision was made to fire” The crew suspected the approaching aircraft was flying within an air corridor as a cover-up strategy. When the aircraft slightly drifted, it tended to support the cover-up hypothesis.

However, the crew never questioned the data that seemed to be in line with an Iranian air attack. If the aircraft did not answer, it could have been due to technical failures or because the aircraft did not receive military frequencies. If the aircraft schedule could not be found in the listing of commercial flights, it could have been the result of flight delays or time zone issues.

From the moment Iran Air Flight 655 appeared on the USS Vincennes’ radar, the scenario of an attack became fixed in the minds which strongly influenced the crew’s ability to make sense of the situation (confirmation bias) and led the Commanding Officer to order firing in the face of a stream of contrary evidence.

- **Reliability of data**
  The Commanding Officer had total faith in the data provided by his crew and never questioned their reliability. Moreover, the crew knew the USS Vincennes had the most sophisticated radar and electronic battle gear in the Navy's arsenal. Yet, two of the most important pieces of information were not correct (fighter jet IFF code and aircraft descending). Such information should have been checked more carefully as they were provided by human operators. However, due to time pressure, hierarchical pressure and inter-individual trust aboard the USS Vincennes, incorrect data were used and interpreted by the Commanding Officer. Mutual trust due to a strong military culture has resulted in a general overconfidence aboard the Vincennes, which in turn led to a lack of cross-check and challenges.

- **Context**
  Over the past year, several U.S. warships had been attacked by fighter bombers in the Persian Gulf. The case of the USS stark which took too long to react led to a change in rules of engagement to avoid such disasters to happen again. That day, the US Intelligence also warned the Commanding Officer of the USS Vincennes of possible air attacks from Bandar Abbas airport. An attack was plausible. The current context significantly influenced sensemaking aboard the USS Vincennes.

- **Individual and collective risks**
  For the Commanding Officer, there were more risks not to act. In the case of an attacking fighter bomber, not firing would have meant putting the ship and lives of his crew at risk. At best, he would have been dismissed for negligence. On the contrary, decision to fire would fall under protective measures while respecting rules of engagement, above all ensuring safety of his crew. Having in mind the consequences of the USS Stark hesitation, Captain Rogers considered the threat was too serious to ignore and decided to fire even if it meant killing innocent civilians.

- **Hierarchy**
  There were strong hierarchical relationships aboard the USS Vincennes. The military culture being based on authority, leaders are always right and it is difficult to question orders. Captain Rogers, the Commanding Officer, did not have to justify himself, nor did he share its understanding of the situation. Some officers have expressed some comments on the situation indeed. The lieutenant pointed out to Captain Rogers that the aircraft was transmitting a "friend" civilian IFF code. On the other hand, the anti-air warfare commander (higher military rank) insisted that Captain Rogers quickly made a decision and recommended to fire. Hierarchy prevented any balanced debate to take place in the Command Center. The headquarters having made clear another Stark disaster had to be avoided, his highest-level officers and the High Command seemed to strongly intimate the firing. Moreover, Captain Rogers did not clearly express his doubts, which might have led his officers to believe he was able to handle the situation on his own.
  Further investigations highlighted the fact that a number of officers aboard the USS Vincennes that day reported seeing the unknown aircraft climbing (and not descending) and did not understand the fire order. However, due to strong hierarchical culture among military personnel, they followed orders without further questioning the Captain's decision.

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- **Time pressure**
  As mentioned earlier, the Commanding Officer of the USS Vincennes only had four minutes to make a decision. At the same time, the Vincennes was dealing with small Iranian gunboats in a surface conflict to which the large warship's crew was unaccustomed. Captain Rogers did not have time to carry out a thorough analysis of all the data or consult other crew members. The aircraft was approaching quickly to the minimum missile range; Captain Rogers had to make sense of the situation and take a decision on his own under time pressure.

6. Practical guidelines for managing the unexpected

In this section, those efforts that can be considered as steps towards an effective management of the unexpected are reviewed, even if they are not always explicitly labelled as such. For ease of presentation, we distinguish organizational perspectives on the one hand, and team and individual perspectives on the other hand (due to the high level of co-operation in complex socio-technical systems, it is indeed often artificial if not impossible to discriminate between these two aspects).

6.1. Organizational perspectives: managing for the unexpected

"The past settles its accounts […]. The ability to deal with a crisis situation is largely dependent on the structures that have been developed before chaos arrives. The event can in some ways be considered as an abrupt and brutal audit: at a moment's notice, everything that was left unprepared becomes a complex problem, and every weakness comes rushing to the forefront". This quote from Lagadec's book (1993) must not be taken as an indication that responses to the unexpected should be entirely predetermined, but as posing a fundamental question: how to make an organization more capable of managing the unexpected through managing (designing) itself for the unexpected? This section is exploring different facets of this question.

6.1.1. High reliability Organizations (HROs)

The work carried out by the current of "High Reliability Organizations" (HROs) did not initially refer explicitly to the management of the unexpected. The HRO concept was initiated at the University of Berkeley, California, in the mid 80's. A group of researchers including Gene Rochlin, Todd La Porte, and Karlene Roberts sought to understand how "organizations" such as nuclear powered aircraft carriers, Air Traffic Control Systems, or nuclear power plants managed to operate such risky processes without any accident over very long periods. They were directly inspired by the "Contingency Theory" (Lawrence & Lorsch, 1967), itself inspired by the theory of complex systems, according to which the structure of an organization is shaped by its interaction with its environment: it is the external set of constraints that dictates the evolution of structures and the internal life of the organization through two phenomena: differentiation (the functional and hierarchical divisions) and integration. (the synergy between departments). The internal life of the organization is entirely dependent on its external constraints. There is little or no autonomy of "actors" in-house. The failure of an actor causing an accident is necessarily the result of a mismatch between the organization and its environment. Conversely, a " high reliability" organization is an organization that knows how to respond appropriately and in time to changes in its environment. But as many structures can satisfy the external constraints, it can be no privileged adequacy model, ie, a "model" of high reliability organization.

However, HROs scholars found that these organizations share a number of features, both in their exposure to risk (risky technologies, error intolerant processes, magnitude of potential consequences, unforgiving political environment) and in their "organizational design" and risk management strategies. These organizational features include:

- A highly centralized, formalized and hierarchical structure, mainly for strategic issues and decisions,

- and at the same time a decentralized, network based, team based, adaptable structure, mainly used for tactical/operational issues and problem-solving, and quickly reconfigurable for emergency management;
- A high level of agreement on the core values of the organization,
- A formal structure of roles and responsibilities with a lot of redundancies and overlaps, and a high level of empowerment of front lines operators to report abnormal events, adapt their behavior and even stop operations in case of imminent perceived danger;
- A clear map of relevant threats, risks and undesirable events, a permanent concern for risk, and the availability of the "requisite imagination" of what could go wrong;
- A capacity to "reorder" and reorganize to deal with new safety threats, through a combination of decentralization and improvisation;
- A high level of technical competence throughout the organization, and a permanent learning and training process, with reference to an elaborated, well documented and evolving set of procedures and practices;
- A "culture of reliability" that instills the values of wariness, care and caution, adherence to procedures, and individual responsibility for safety throughout the organization;
- The provision and maintenance of slack, buffers, stocks, to provide robustness against unpredicted events.

These features were not explicitly seen by the first generation of HROs scholars as facilitating the management of the unexpected, but more broadly as allowing an organization to respond appropriately and in time to changes in its environment. Nevertheless, these HRO features are appropriate to prepare an organization coping with the unexpected. Furthermore, the HRO school of thought evolved in the late 90s when researchers like Karl Weick, Kathleen Sutcliffe, and David Obstfeld's (2001) systematically reviewed the literature on high reliability and focused on the management of the unexpected by teams. They showed how high reliability was grounded in efforts to organize in ways that enhance the patterns of attention across the organization. They described processes of "collective mindfulness" (preoccupation with failure, reluctance to simplify interpretations, sensitivity to details, commitment to resilience, deference to expertise). This perspective was particularly elaborated by Weick and Sutcliffe's (2001) who explicitly addressed "Managing the Unexpected" (the title of their book) through the concept of "mindful organizing", in which they describe how people "make sense" of unexpected situations, interact to "enact" and update a shared understanding of the situation and simultaneously develop a capacity to act upon that situation. They emphasized the role of leaders in shaping the social infrastructure of the organization in a way that facilitates that collective "sense-making" and the emergence of a shared "culture" at different organization levels (teams, departments, company).

6.1.2. Normal Accident Theory (NAT)

High Reliability Organization theory is often seen as the "optimistic" view in contrast with the "pessimistic" Normal Accident Theory (NAT). The father of NAT, Charles Perrow, was involved in the Three Mile Island nuclear accident investigation, and he theorized his understanding of this accident and generalized it to other domains in his famous book (Normal Accidents, 1984). Perrow's thesis is that modern complex socio-technical systems such as nuclear industry, aviation, or chemical industry have reached such a level of complexity, characterized by tight coupling (time-sensitive invariant sequences, complex interactions and propagation of effects, lack of slack, intolerance to deviations), that whatever the efforts invested and the level of quality attained in terms of operations thoroughness and management efficiency, accidents will inevitably happen as the outcome of the cascading accretion of invisible and unpredictable interactions. In brief, accidents in such complex systems are the “normal” result of the real system’s behavior. In other words, Perrow claims that complexity is uncontrollable, hence inherently unsafe, while HROs believe that complexity can be outmaneuvered by … complexity (auto-organization, awareness, sense-making, imagination, flexibility, adaptation…).

Our goal here is obviously not to compare HROs and NAT[9] and to assess who is right and who is wrong, but rather to understand what can be useful in both these theories to better manage the unexpected. Perrow being "pessimistic" about controllability, he does not propose a solution to handle the unexpected, except to refrain from designing and developing complex systems generating the unexpected. It is doubtful that this strategy would actually allow to avoid the unexpected in our modern large-scale technologies, but it would indeed very likely decrease the frequency, as well as the disruption power of the unexpected, and make sense-making and recovery much easier. Consequently, it seems reasonable to follow Perrow in promoting the principle of "maximum simplicity" and of “downsizing” in the design of high risk socio-technical systems.

6.1.3. Resilience Engineering (RE)

The purpose of Resilience Engineering is to “engineer” resilience features into the design of organizations. We have briefly reviewed the concept of resilience at section 4.6. Resilience is the ability to control or adapt to changes and disturbances, both expected and unexpected. This notion is therefore particularly relevant to think about the management of the unexpected. From an organizational perspective, an obvious question here is how does Resilience Engineering compare to HROs, and what suggestions does it make for the management of the unexpected that would differ from HROs’ suggestions?
As a matter of fact, HROs and RE movements are similar schools of thought. While the respective founders of these movements may have in average different backgrounds (mainly organizational sociology and psychology for HROs, mainly systemic safety and Human-Machine cognitive systems reliability for RE), they share a common vision of organizations as complex systems and they have reached similar conclusions in terms of “positive” organizational features. RE supporters approve all the “organizational reliability” features described by HROs, and HROs supporters (particularly the “second wave” including Weick, Sutcliffe) explicitly refer to resilience and to the management of the unexpected in their work.

Actually, the main difference between HROs and RE could be simply equated to the difference between “reliability” and “resilience”. Reliability is robustness[10] to failures. Resilience is the ability to manage the inevitable trade-offs between robustness and fragility of the different properties (performance component) of a system, in order to manage disturbances, anticipated or not, without significant degradation of the main ones, according

[9] For a comprehensive comparison illustrated in the field of nuclear weapons, see Sagan (1993)
[10] A property of a system is « robust » to a given set of variations if it is invariant for this set. The notion of robustness hence implies a clear identification of the system at stake, of the property concerned, of the variations against which robustness is assessed, and of the metrics used to assess invariance. A system generally has robust properties and fragile properties for the same variation. A nuclear plant safety can be robust to earthquakes but its productivity is fragile to them, as safety is then obtained by an automated shutdown. A given property can be robust to some kind of variations and fragile to others. A population can be robust for one kind of flue virus and fragile for a different one.

to its established hierarchy of goals and values. This includes the capacity to take *benefit* of variations to improve performances (the word resilience comes from the latin re-silere: to rebound). In other words, HROs people are seeking to understand how an organization can efficiently prevent failures and safely recover from them, while RE people are rather interested in how an organisation builds daily successes (e.g. safety) in spite of, and often with the benefit of, variations and disturbances. Metaphorically, HRO is a healthy life style, permanent wary about one's health, recurrent medical checks, early detection and medication. RE additionally includes exposure to experiences that make us stronger and stimulate the development of immunity: exposure to pathogens, vaccination, allergy desensitization, "mithridatisation". From an organizational point of view, one could summarize the difference as follows: HROs are structured as a "generative authority", encouraging their staff through empowerment and a "just" culture"; whereas RE rather bets on networks and auto-organization.

6.1.4. Emergency management plans and crisis management

Emergency management plans have become a natural component of risk management. They concern that particular category of the unexpected that we called "the ignorance of when", i.e. well identified situations in which it can be anticipated that the level of threat on lives and/or property will be exceptionally high, while their time of occurrence is unpredictable. Emergency plans can be established at national or regional level and then mostly address natural disasters (fires, floods, earthquakes, tsunamis, cyclones), health disasters (epidemics, food poisoning), uncontained industrial disasters with large scale pollution (nuclear, chemical, offshore oil operations) or severe transportation accidents (rail, air, road, sea). They can also be established at a company or factory level, and then specifically address the serious accidents identified as possible for the activities at stake.

Emergency plans anticipate that the normal functioning of the company or the whole society will be overwhelmed and disorganized by listed exceptional events, and they include procedures to overcome such disorganization: emergency (re)organization principles, identification of key players and decision makers, predefinition of cooperation and assistance of civil protection and emergency services and hospitals, involvement of exceptional means (e.g. army), and the like. Regardless of the care taken in their design and completeness, emergency plans have two sensitive points: the initiation rule and the testing/training of the plan. Determining when, in the evolution of a situation, an emergency plan should be activated is rarely easy, and all the more difficult that the emergency plan is comprehensive and heavy and the situation ambiguous, i.e. different from anticipated. As far as the second issue is concerned, most emergency plans recognize the necessity of appropriate testing of the plan, as well as the necessity of an appropriate training of the dedicated staff, and they include provisions for this. For both issues, recurrent practice is a key condition of efficiency, and the challenge is to do it under realistic conditions, including a reasonable dose of surprise. Otherwise, there is a high risk of wrong learning, developing ingenuity and overconfidence in the plans: real emergencies rarely follow the plans, which does not mean that plans are useless, as illustrated by Weick's wrong map story!

While there are few specific standards (CWA 15931-1:2009 Disaster and emergency management), a number of guidelines for Emergency Planning are available from various organizations such as ASIS, FEMA and the Emergency Planning College. Free access software tools are available on the internet. More detailed information can also be found on http://en.wikipedia.org/wiki/Emergency_management.

6.1.5. Safety Culture improvement

As already mentioned, the concept of 'safety culture' is particularly attractive when discussing the management of the unexpected, since the unexpected exacerbates the role of informal organizational features in the organization's ability to respond. Hence it seems natural to include "safety culture improvement" efforts in a review of approaches to improve the management of the unexpected. Many such approaches have been developed within different industries (Nuclear, Aviation, Off-shore Oil, Chemical, Manufacturing, Hospitals) since the late 80's, after the concept of safety culture had been introduced in a Chernobyl accident report (AIEA 1988). They usually start with an **assessment** of the current safety culture, followed by steps to make it **change** and shift towards a "**better**" one. This questions what "better" actually means, and additionally to what extend that "better culture" would allow a better management of the unexpected.

What would a "better" culture look like?

A culture is a multi-dimensional concept, so it cannot be measured (or rated) then compared to the next one (like a point in a three coordinate space cannot be declared "better" or "superior" to another one). This is only possible if a hierarchical order has been defined within the dimension's space of a safety culture. The following table represents one of the first attempts to define such a hierarchy, initially proposed by R. Westrum in the mid 90's, and based on "how organizations process information".

Table 1 How organisations process information

Pathological	Bureaucratic	Generative
Power oriented	**Rule oriented**	**Performance oriented**
Low cooperation	Modest cooperation	High cooperation
Messengers shot	Messengers neglected	Messengers trained
Responsibilities shirked	Narrow responsibilities	Risks are shared
Bridging discouraged	Bridging tolerated	Bridging encouraged
Failure→ scapegoating	Failure→ justice	Failure→ inquiry
Novelty crushed	Novelty→ problems	Novelty implemented

Westrum (2004). A typology of organizational culture

Actually Westrum did not present it as a hierarchy but as a mere typology. However, this typology was suggestive enough of a hierarchy, and was indeed subsequently elaborated into a hierarchy through the notion of Safety Culture Maturity (SCM). Among the existing variants of this notion, Hudson's contention (2003, 2007) is that a safety culture develops (improves) through five levels of maturity:

- Level 1: Pathological (Why waste our time on safety? Information supports power and glory. Loyalty and conformity is maintained through intimidation We react to problems by denial and encapsulation)
- Level 2: Reactive (We do something when we have an incident; Information is "managed" to ensure we conform to organisational standards (e.g. target incident rate); We

focus on finding who is at fault and using appropriate discipline; Safety would improve if employees were more careful)

- Level 3: Bureaucratic (We have systems in place to manage all likely risks. Information is controlled by departments to make them look good; people responsible for making errors are treated with justice; In reaction to incidents we seek local fixes, treat symptoms not root causes)
- Level 4: Proactive (We are always on the alert for risks that might emerge; Information is important and we work hard to capture it and understand what is going on. Our outcomes are better than our peers; We are still surprised by some events).
- Level 5: Generative: (We know why we do not have incidents; Information supports the mission and flows freely, honesty is valued; In response to incidents we seek a global fix, we try to fix every example of a problem, and share information with other stakeholders; We enquire and get to the root cause of problems).

Safety culture assessment methods

Current safety culture assessment methods mainly include self-completion questionnaire surveys, aiming at the identification of strengths and weaknesses in the current culture, as well as at allowing a benchmark with comparable organizations and creating a baseline to measure future evolutions (Carroll, 1998). Survey questionnaires need to be tailored to a specific domain, and have been developed for virtually all activities (e.g. Occupational Safety in Manufacturing, (Brown & Holmes 1986), Chemical industry, (Donald & Canter, 1994), Off-shore (Mearns & al.1997), Nuclear industry (Lee, 2000), Aviation (Meshkati, 1997; Gordon & al., 2006).

However, experience of many companies has shown that the gross outcome of these surveys is difficult to use as such to make decisions, and needs to be interpreted. Hence surveys are generally complemented by discussion workshops or focus groups during which the results of the survey are discussed with a representative sample of the staff. Also interviews are conducted, as well as a review of relevant documents (e.g. SMS documents, incident investigation reports, safety dashboard), and real activity observations. Safety culture assessment processes can be either contracted to an external consulting organization (with the benefit of a more neutral position and benchmark expertise) or conducted internally by an ad hoc team (e.g. IAEA has developed guidance material to assist nuclear plants to do so).

Safety culture improvement strategies

As already discussed in section 4.7, a (safety) culture is a dynamic and very stable balance, and is difficult to change. It has been formed over decades of professional life interactions and cannot be changed by a few workshops or trainings. A (safety) culture can only change if there is a deep change in the processes that (re)generate it. For example, staff perception of safety values and management commitment to safety are based on their real life experience: daily interactions with managers, assigned performance targets, actual practices as tolerated or encouraged, real incentives, actual rewards and practical rules reinforcement measures. Hence something must change simultaneously in all these areas. First and above all, senior managers must understand the need for change and really want this change. Nothing will happen otherwise. This usually implies a change of their mindset, which may result from various triggering factors: an inspiring benchmark, the recognition that the prevailing safety strategy provides disappointing results, a catastrophic accident or a near miss, a dynamic safety manager, and the like. Usually the next step is a strong communication by the senior management about their willingness to impulse a cultural change, and the launch of a top down process, including training for all managers and supervisors about safety leadership and the new desired values, changes in the (safety) performance indicators, changes in the reward/punishment policy in connexion with a promotion of organisational learning (encouragement to report errors and incidents, “just culture” policy, reinforcement and modernisation of incident/accident investigation methodologies, and training for front line operators about the new “rules of the game” and corporate expectations. It also includes practical changes in managers’ behaviour, such as frequent visits of the worksite, safety briefings, debriefings of incidents.

However, this top down process alone will generally not produce and sustain the expected outcomes. It is highly recommended to complement it with a bottom up process in which all front line operators are directly involved in a collective critical review of their current safety practices, and progressively build a consensus based on the desired values on the needed changes concerning their own practices, procedures, and work contexts. This is on condition to really trigger a shift from a traditional, hierarchical and centralized management, based on authority, towards more empowerment of the workforce to handle local contingencies.

Safety cultures and the management of the unexpected

From our review of the safety culture rhetoric in 4.7, it derives that a safety culture change is not, in itself, necessary good for the management of the unexpected. As already mentioned, most current safety culture improvement approaches more or less share the same objectives, as summarized by Reason (1997), and seek to develop an informed, reporting, just, flexible, and learning culture while progressing through the Westrum/Hudson maturity levels from pathological to generative. Such a march towards higher levels of maturity would certainly improve the capabilities to handle the unexpected, nevertheless, in the prevailing safety culture models and corresponding measurement techniques, a very normative culture, imbued with a ‘total predetermination illusion’ could still be assessed as a mature safety culture. It seems reasonable to argue that the level of consideration paid to the management of the unexpected by a safety culture within a specific domain should be proportionate to the level of uncertainty prevailing in that domain. A safety culture should explicitly address the management of the unexpected as such, and include the organizational recognition that unexpected events will happen, and the recognition that a mere compliance to rules and procedures cannot be sufficient to handle the unexpected. A major implication of such recognition is that adaptability processes should be distributed throughout the system and bottom-up rather than centralized and top-down. Safety culture improvement efforts should then focus on the sharing of values, priorities and interpretation rules that allow a coherent control of trade-offs at all levels of the organization.

6.2. Team and individual perspectives

This section provides a review of available training, methods, and tools for managing the unexpected which mainly aims at improving collective decision making.
Two main approaches, further divided into two different aspects, are distinguished:

- Improvement of intrinsic abilities of individuals
- Generic training
- Practical training
- Use of support tools for sense and decision making
- Reasoning methods
- Decision making support tools

6.2.1. Generic training in managing the unexpected

Along with technical knowledge and experience, other factors need to be taken into account: they correspond to non-technical, cognitive and relationship skills of individuals.

Leadership training

Leadership training is intended for decision makers in order to train them in supervising and managing crisis. Such training is based on traditional theoretical courses to address the following topics:

- Duties of decision makers: preparing the team, developing skills, making well through-out decisions, ensuring tasks are correctly achieved etc.
- Respect for the team: knowing their subordinates, giving information, developing team spirit, giving everyone adequate orders etc.
- Leading with integrity: knowing oneself, setting a good example, taking responsibilities etc.
- Qualities of a good leadership in crisis situation: ability to mobilize, interests of the team etc.
- Factors leading to poor decision making: stress, ambiguous authority, insufficient preparation etc.

Although such leadership training aims at improving decision making of leaders in the face of unexpected situations, it remains mainly both theoretical and preventive, through the listing of potential risks, without really providing concrete methods or tools to cope with those risks. Nonetheless, leadership style and non-technical skills play an important role in managing the unexpected, and leadership training sessions address those themes to raise leaders' awareness on such issues.

Crew Resource Management (CRM) training

Since the 1980's, the aviation industry has developed and mandated an overall method to train operators in a set of Human Factors issues, called "Crew Resource Management" (CRM), or Team Resource Management (TRM). CRM/TRM is a training that fosters the efficient use of all available resources within the team to improve safety, through the improvement of Non-Technical Skills. Those skills include personal qualities as well as cognitive and interpersonal skills (Flin et al, 2008). CRM training differs from traditional theoretical training in the following aspects:

- The training is global and deals with a large number of Human Factors issues:
    - Communication
    - Interpersonal skills
    - Situation awareness, uncertainty management
    - Problem solving, decision making
    - Threat and error management
    - Adherence to procedures: needs and limitations
    - Leadership, collaboration, synergy
    - Stress management
    - Teamwork
- Training sessions are based on actual examples, talks and debates, videos, role plays etc.
- Training sessions involve operators from across all types of activities and hierarchical levels.
- Sessions are facilitated by peers rather than instructors, to allow for inter participant's confidence building and foster honesty about real life professional practices under discussion.

CRM training aims at creating a collective dynamic to promote safety culture and improve collective reaction skills when confronted with the unexpected. It is based on individual and collective awareness in order to develop skills and change attitudes within a group. CRM training is currently a mandatory requirement in the civil aviation industry. Such training is now being extended to other safety-critical domains (Energy, Rail, Healthcare etc.), including the military. In some advanced evolutions of this kind of training, the main outcomes from discussions addressing weaknesses in the safety process are summarized and communicated to the management, who commit themselves to act upon these issues.
Although it does not necessarily offer practical solutions in terms of reasoning and decision making methods, CRM training corresponds to a more global and collective approach to improving reactions to the unexpected. It is based on meta-knowledge and individual involvement to raise awareness and bring about changes in collective behaviors beyond mere prevention. CRM training also includes some basic concepts and support tools for decision making such as DODAR and FORDEC (see further). Even though results of such training are difficult to quantify in terms of enhanced reaction to the unexpected or number of errors, indirect measurements have shown CRM training actually changes behaviors and reactions of most participants.

Creativity training

In the management of unexpected events, players are required to show creativity, either to anticipate possible scenarios and corresponding barriers or imagine real-time solutions facing the unexpected. Coping with the unexpected often means finding a solution to a problem that has no straightforward solutions. Operators rely on their knowledge, improvisation and imagination skills to create a totally new and original solution. As suggested by Comfort (1999) and Weick (1993), ability to adapt to the unexpected, sense-making and creativity are connected.

A number of approaches have been suggested to foster creativity, with no real consensus. Nonetheless, eight cognitive abilities can be identified that play an important role in creation (Lubart et al., 2003): ability to identify and define a problem, selective encoding, selective comparison, selective combination, divergent thinking, self-evaluation of progress toward the solution and cognitive flexibility. From those eight abilities, a number of methods and specific tools have been developed to improve individual and team creativity:

- Problem reformulation
- Association of ideas techniques
- Analogy with other domains
- Combinatory techniques (cross-tabulations)
- Divergence (multi-directional thinking, problem alteration etc.)
- Projective techniques
- Brainstorming and “brainwriting”
- Random methods based on chance
- Oneiric methods (e.g. collective day-dreaming)

There are many existing methods and tools available to improve creativity skills. Among those methods and tools, the most known are:

- Rational methods: the TRIZ or ASIT (Advanced Systematic Inventive Thinking) methods by Genrich Altshuller, the Discovery Matrix (by Abraham Moles).
- Group methods: Brainstorming (Alex Osborn), Creative Problem solving (Alex Osborn & Sid Parnes), Challenge storming (Jean-Louis Swiners & Jean-Michel Briet), ideas collecting, brainwriting etc.

- Generic methods: PAPSA (Hubert Jaoui), the 5 whys (Sakichi Toyoda), 4 roles of creativity (Roger Von Oech), Mind mapping (Tony Buzan), SCAMPER list of questions (Alex Osborn) etc.

These methods are usually presented during conferences or seminars on creativity and involve group work and role-playing. The aim is to bring participants to "think outside the box" and see the problem from a different perspective. However, they are mostly used in competitive industries to promote research and innovation, strategic reflections, and marketing creativity rather than directed to improving the management of unexpected or crisis situation. Moreover, it has not been demonstrated yet that using one of these methods actually enhances creativity in operational situations. All the above methods only address human cognition to improve creativity (knowledge, intelligence), while other aspects such as emotional state (e.g. stress), personality and motivation are contributory factors and should also be taken into account (Lubart, Mouchiroud, Tordjman & Zenasni, 2003).

6.2.2. Practical training in managing the unexpected

Limitations of theoretical training in crisis management have been widely discussed in the literature. Concepts and methods addressed during formal lectures may not be easy to apply in an operational setting, especially when time constraints are tight. In this respect, Klein (1997) suggested the most direct way to improve strategic abilities in decision makers is practical training. Different types of practical training are reviewed in the following which all aimed at enhancing reaction to the unexpected.

Simulation

Studies have shown that 90% of decisions are made based on personal experience of similar situations, without even considering alternative solutions. In this regard, one approach to training in decision making under unexpected events entails subjecting decision makers to a large variety of concrete situations, especially those related to rare events.

In high-risk domains, these types of situation are difficult to recreate in the field. This is why training methods in simulated environment are used. The aim is to make participants develop a large number of decisional strategies and experiences so as to improve their reaction time when confronted to the unexpected, by automating the process of decision making. Simulation is currently used in many domains:

- Mandatory and continuous training of airline pilots on simulators (CRM training or qualification on new aircraft type)
- Continuous training of train drivers on simulators, such as SIMBA (French National Railways).
- Simulation software for training in natural disasters management, such as "Urban-Risk".
- Simulation software for training in tactical decision making, such as "Commander's Quest" used by the Norwegian officers school (Bakken, 2002).

Practical training in managing the unexpected through simulation has several advantages. Real conditions of operational situations (physical environment, dynamic and time pressure) in which the unexpected can arise can be accurately recreated (ecological validity). Simulation also enables real-time control of numerous parameters in order to confront operators with a large number of possible scenarios, even the most unlikely situations.

However, simulations also have drawbacks:

- Such simulations are expensive and often require heavy logistic.
- Rare events can be simulated; however, rare does not mean unexpected.

- As soon as they find themselves in a simulator, trainees expect something to happen, which minimizes the surprise effect. It is difficult to create real surprises in a simulator, and evn more to maintain this capacity on a long term basis.
- Simulation goals often entails subjecting operators to a great variety of situations with the aim to cover all possible cases, which is obviously not possible, and generates perverse effects (trained people will be even more destabilized when facing a real surprise).

The "Staff Ride"

The staff ride is an old concept (used as early as the nineteenth century) which consists in identifying an actual critical event (a battle or a disaster for example) and using it as teaching medium. The purpose is to "put participants in the shoes of the decision makers on a historical incident in order to learn for the future" (Useem et al, 2005).
Trainees are asked to think, compare and analyze action modes in the particular context of the critical event considered, in order to learn lessons with regard to decision making issues. This method enables the development of prospective and analytical mind, as well as creativity when confronted with unexpected events.

The staff ride concept is three-fold:

1) Reminding the context of the event
2) Visiting the actual site to confront with reality of the field.
3) Collective analysis of the event.

The staff ride method is very similar to traditional analysis of events, however showing higher ecological validity by involving actual confrontation with the field. Overall, the method remains quite educational and does not really immerse decision makers in actual crisis situation.

Tactical Decision Games

Practical training in decision making may be either expensive (e.g. simulations) or little realistic (table-top exercises). To overcome those drawbacks, another approach has started to spread out in high-risk domains: Tactical Decision Games (TDG).
This type of training consists in combining a simple case study with a dynamic and realistic simulation. For this purpose, participants are given a scenario they have to work out. A "facilitator" provides participants with a number of feedbacks.

The scenario should include:

- A problem or a dilemma with no unique solution
- A specific role is assigned to the participants for the game
- Some limitations: typically, quantity of information is limited to create high level of uncertainty. Time is also limited and may even vary in the course of the game.
- A time for analysis and criticism: decisions made by the participants are discussed, criticized and shared with other participants to learn the lessons.

The role of the "facilitator" is to help play the scenario, create dynamics in the game, make it appear more realistic, and help the participants learn from this experience. In this regard, the facilitator should:

- Provide feedbacks by adding information during the game (or modifying data)
- Help participants assess their performance by questioning them or criticizing their strengths and weaknesses.

Tactical decision games are a quick and simple way to practice and operationalize knowledge acquired on decision making. They also represent a good opportunity to develop collective understanding of a situation as well as collective problem solving. Tacti-

cal decision games also enable participants to build a catalogue of decision making models that could be easily and quickly reused in emergency situations. Non-technical skills such as communication, stress management and teamwork are also addressed during tactical decision games.
Tactical decision games are now officially included in some decision making training programs such as those for "US Marine Corps squad leaders" (Klein et al, 1997) or those for firefighters (McCloskey, Pliske & Klein, 1997). Participants of such programs reported they felt better prepared to make difficult decisions in unpredictable contexts and under time pressure (Klein, 1998).

This type of training is also used to introduce Royal Netherlands Air Force officers to critical thinking (see further). It was shown that after a few hours of training, officers improved their ability to assess the situation and make sound decisions under challenging conditions (Van den Bosh & Helsdingen, 2001; Cohen, Freeman & Thompson, 1997). The TDG method is relatively inexpensive and easy to implement while keeping realism. Experimental studies in penitentiaries as well as in the nuclear industry have shown that the TDG method improves speed and efficiency of decision making under uncertainty (Crichton, Flin & Rattray, 2000).

Serious Games

Serious games are educational and serious software. Most of the time, they are free or quite inexpensive, aiming at raising awareness of a wide audience. Serious games are used in a large variety of domains: communication, education, training, marketing, information, religion, politics, healthcare, safety etc.

Serious games have two main objectives: entertainment and serious learning. They are based on teaching techniques applied to facilitate learning mechanisms throughout playing. The player gets "direct" feedbacks on his/her wins and on the results of his/her strategy, as well as "indirect" subliminal awareness messages (e.g. about sustainable development, world hunger, safety, health etc.)

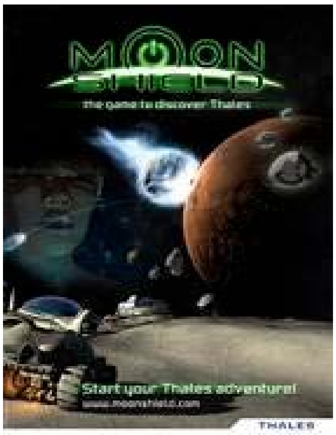
A variety of situations from unexpected events to regular and irregular threats can be played. Mechanisms of crisis management can be trained both individually and collectively.

Examples:

- "MicroSim" is a serious game intended for medical students to train them in emergency situations (application of procedures and initial diagnosis).

"MicroSim" – Serious games for medical students

- "Moonshield" was developed by THALES. Players are placed in a crisis situation they have to work out. The aim is to use one's knowledge of different professions and identify the best recruitment strategy for THALES.



"Moonshield" – Serious games for crisis management (http://www.moonshield.com/)

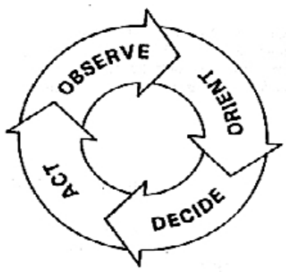
As for simulation techniques, training in managing the unexpected through serious games allows more or less accurate recreation of actual crisis conditions. It also enables real-time control of many parameters so that many different scenarios can be created and played.
Serious games benefit from the growing success of video games, especially toward young people. Video games are no longer limited to entertainment; they are now also used as educational medium. More and more organizations such as the U.S. army, universities, and large corporations also have started developing "serious games" to train their staff to handle specific situations. However, video games tend to remain stuck in the current economic model which mainly focuses investments on the entertainment industry. Serious games would need further financial involvement if they are to be used as real training medium.

6.2.3. Reasoning methods for managing the unexpected

In order to improve decision making skills, a number of reasoning methods for coping with unexpected situations have been developed, mainly for the military so as to improve officers' reaction skills. These methods are based on cognitive models of decision making.

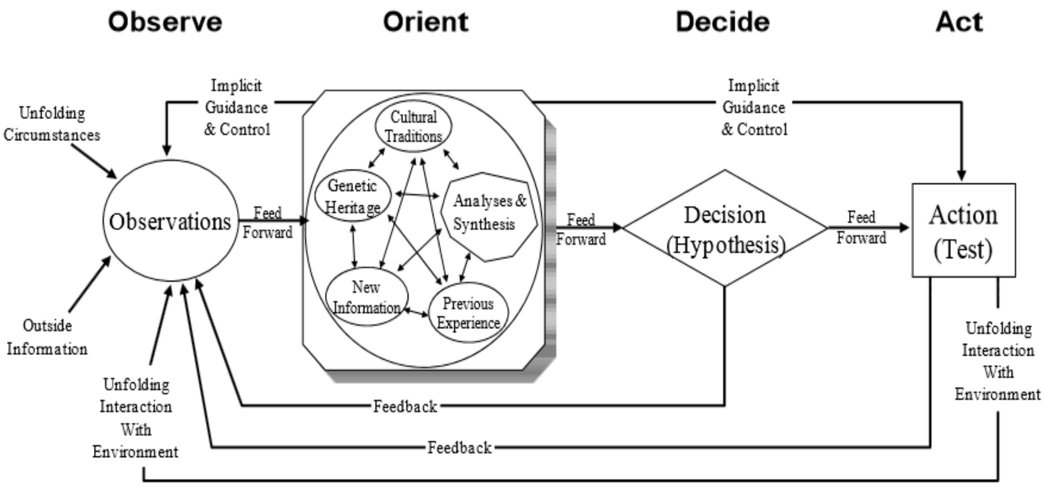
The OODA cycle

Decision making in emergency situations is nothing new and has already been particularly studied in the military. One of the first formalization of constrained decision making under time pressure was proposed by a military instructor in the 1950's: the OODA cycle. The OODA concept is now taught in military academies and used by most armies worldwide.



The principle is to get the upper hand over the enemy by passing through a 4-stage cyclic process which enables faster decision making whatever the situation, including unexpected events (Guitouni et al, 2006). The four stages are:

- Observe: consists in gathering information and data from the developing situation, as well as observing how external information impacts action in the field.
- Orient: corresponds to filtering of observational data about the current situation. This stage is based on operators' knowledge and experience. It highly depends on the person's cultural heritage and personal history. Two different people would not share the same model of the on-going situation.
- Decide: consists in the choice of a course of action. In the OODA model, decision making is regarded as a hypothesis. This means it is neither a thorough analysis of the whole set of information, nor a deterministic calculation of action development. It rather means assuming that one action is achievable, better than other possibilities, and that it will lead to good results. The "hypothetical" decision of action needs then to be tested.
- Act: implementation of the selected course of action. In other words, this entails testing the hypothesis from the previous "Decide" stage. Once implemented, the action will inevitably differ from its model ("reality test"). Results of this test will be observed and will serve as input data for the first stage of the next OODA cycle (start of a new OODA cycle).



The OODA cycle (Boyd, 2001)

As different people would not share the same model of the situation (due to differences in cultural references, personal history etc.), a blockage in decision making can arise, such as the so-called OO-OO-OO trap. In an OO-OO-OO cycle, decision makers process data without being able to identify which pieces of information are relevant; so they wait for more data and continue observing. New incoming data do not allow them to decide either; so they continue observing again and again etc. Decision makers are trapped in an OO-OO-OO cycle ("Observe-Orient") which hampers quick decision making.

The understanding of the OODA cycle should in theory allow decision makers to:
- Get out of the OO-OO-OO trap and avoid inability to decide.
- Quickly re-assess their decisions through the "reality test".
- Anticipate others' reasoning and pre-empt it.
- Accept chaos of action and act in order to get a better understanding of the situation and make a decision.

Some variants have been developed in the aviation industry: the DODAR (British Airways) and the FORDEC methods are taught during some CRM trainings. The aim is to offer a reasoning method which could be applied whenever standard operational procedures are no longer relevant ("abnormal situations"):
- DODAR: Diagnosis, Options, Decision, Assign task, Revision
- FORDEC: Facts, Options, Risks/Benefits, Decision, Execution, Check

When confronted with unexpected and ambiguous situations, the OODA model suggests to act and observe ("reality test") in order to make sense and build a better representation of the situation (Boyd, 1976). However, in the military as well as in other safety-critical industries, any action that would not immediately be relevant could quickly show itself to be catastrophic.

Although the OODA concept is interesting to understand the risks associated with collective decision making (sharing the same representation of the situation within a heterogeneous group, the OO-OO-OO trap, inability to decide etc.), it does not provide any concrete method to overcome those risks when they occur. Nonetheless, the OODA cycle provides an overall model for collective decision making that summarizes the different processes involved in "Command and control" centers.

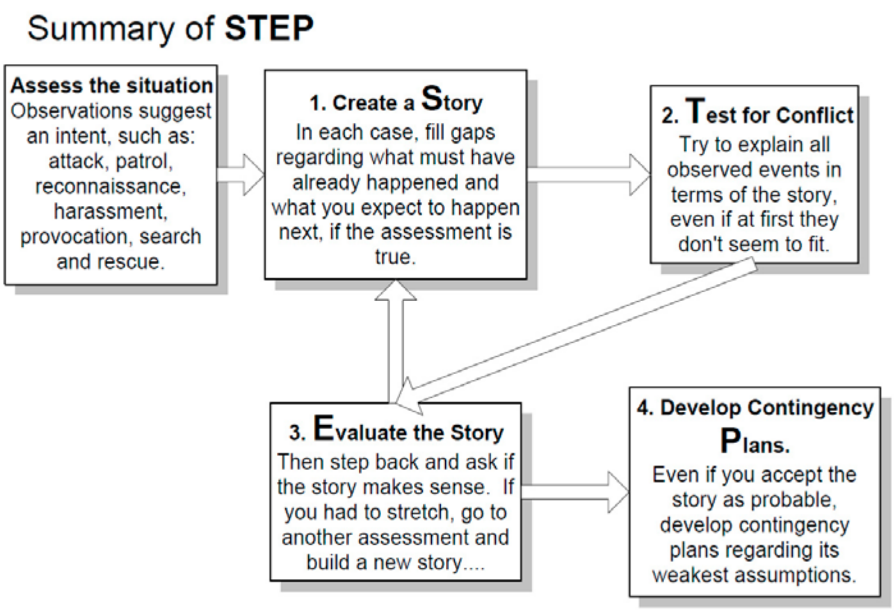
Critical thinking

To overcome the shortcomings of the OODA concept, another approach has been developed, based on the “Naturalistic Decision Making” model (Zsambok & Klein, 1997). In this model, decision making is regarded as a dynamic process of problem solving in which the decision maker assesses the situation by collecting data and creating a representation of the situation in the form of a scenario. Plausibility of this scenario is then tested and assessed. If it appears relevant, an action plan is to be created and implemented based on this scenario.

The theory of naturalistic decision making suggests training should be based on the model of expert decision making (Cohen, 1998; Klein, 1998). When confronted with a novel situation, experts differ from novices in their ability to achieve better assessment and criticism of available data in order to create a scenario (Helsdingen, Bosch & Van den, 1999; Cannon-Bowers & Bell, 1997). This is the “critical thinking” concept.

Critical thinking is the “intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief and action” (Fischer & Scriven, 1997).

A detailed model by Cohen et al (1996) explains how critical thinking works: in the event of unexpected occurrences, a recognition/metacognition process is triggered. Based on this principle, Cohen et al (1996) have developed a new training method for decision makers in crisis situations which seeks to improve their ability to reconstruct representation of the situation:

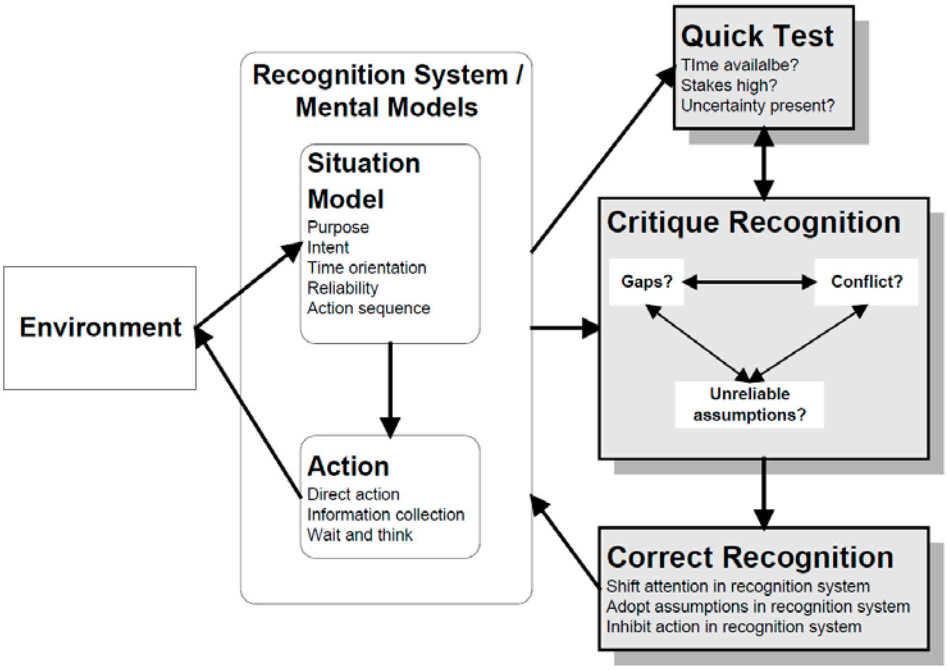


A cycle of four steps for critical thinking (Cohen et al, 1996)

Reconstruction of mental model facing a novel situation is achieved through three meta-processes: critiquing, correcting, and “quick testing”:

- Self-criticism: challenging one’s representation of the situation and plausibility of scenarios by determining whether available information is complete, whether pieces of information do not conflict with each other, and whether they are reliable.

- Self-correction: if answers to “self-criticism” questions are not acceptable, one’s representation of the situation should be corrected by collecting more information, changing point of view, or adjusting one’s suspicion level toward initial hypotheses.
- Quick test: continuously asking oneself whether the situation is unprecedented or familiar, whether one’s hypothesis is acceptable with regard to cost and time, and whether the risk of error toward one’s hypothesis is not too high.



The Recognition/Metacognition model and its three basic metacognitive functions: Quick Test, Critiquing, and Correcting (Cohen & Thompson, 1999)

The training process in critical thinking requires two complementary steps:
- Theoretical training: presentation and teaching of concepts.
- Role-playing: use of scenarios involving high level of uncertainty. Throughout practical exercises, decision makers can develop decision making strategies based on critical thinking.

The critical thinking method is relatively recent. However, its benefits have already been assessed through experimentations for a decade. The main benefits of the critical thinking model are:
- Larger number of questions considered by decision makers to assess unexpected situations
- Enhanced detection of contradictory information
- Larger number of explanations generated by decision makers as to inconsistencies
- Larger number of alternative solutions
- Improvement in the ability to rule on the value of self-assessment
- Better assessment of information confidence level

These benefits have been demonstrated in several domains (military pilots, maritime, commercial pilots). Although critical thinking is initially aimed at improving individual decision making, a few studies have also successfully applied it to collective decision making, for example with the Royal Netherlands Air Force and the US Office of Naval Research (Van den Bosch & Helsdingen, 2004; Freeman & Hess, 2003).

Based on cognitive "natural" models, the critical thinking method can easily be translated into operational contexts with measurable benefits (Cohen, Adelman & Thompson, 2000). However, the method has been mainly studied within the individual framework and further research is needed to take into account collective issues within a heterogeneous group. The method also needs to be validated in real setting as well as over the long term.

Sensemaking

As mentioned earlier (*see "Reactions to the unexpected"*), collective reaction to the unexpected largely depends on the group's ability to make sense of the situation. This process, named "sensemaking" is the "*deliberate effort to understand events. It is typically triggered by unexpected changes or other surprises that make us doubt our prior understanding*" (Klein et al, 2007). Many studies have been directed toward the rationalization and improvement of the sensemaking process by proposing factual implementation methods.

Sensemaking methods are based on the systematic analysis of available data in order to achieve sufficient understanding of the situation to decide on the best course of action. The aim is to support detection of weak signals and avoid decision bias. Snowden & Klein (2007) have reviewed a number of existing methods:

- **Crystal Ball**

  "The Crystal Ball was originally developed by Marvin Cohen to enable constructive criticism, either at individual or group level. The crystal ball aids in identifying a gap in the available data regarding an initial assumption. In a team setting, people are often resistant to criticizing the ideas of others. The Crystal Ball provides a format that supports a productive critique of assessments, leveraging input from all team members. With a Crystal Ball technique, the group is told that the initial assessment of situation is wrong. Through mental simulation, the group attempts to come up with alternative assessments based on the given situation. The intent is to compel team members to think differently in order to uncover critical flaws and areas of concern that are otherwise ignored. Once this is done, the group can look for more than one possible solution." (Snowden & Klein, 2007) The crystal ball technique is useful in generating explanations of conflicting data. It shows how to reinterpret the new information or to create a new situation model that accounts for all, previously conflicting information (Cohen et al, 1996).

- **Ritualized Dissent**

  "This method was developed to overcome problems of group-think and pattern entrainment. It should not be confused with the more commonly known method of Devil's Advocacy in which dissenting opinions are introduced. In ritualized dissent, different groups of people engage in the same process and then send a spokesperson to another group to present their ideas. Following completion of the presentation the spokesperson ritually places his/her back to the audience and is not allowed to explain, argue or justify their position while the audience engage in an all-out attack on their ideas. In effect, learning takes place in two ways: (i) in being forced to listen without response, the person subject to attack is not mentally preparing a rebuttal (as would happen in normal discourse) since no rebuttal is allowed, and (ii) the audience, in criticizing the other person's position, often realize flaws in their own arguments. The ritual turning of the back by the person on the hot seat helps to depersonalize the criticism and to increase the attention of the person on the hot seat who has no eye contact with the critics." (Snowden & Klein, 2007). Ritualized dissent encourages exposure of flaws in own argument through forming critique of others, leading to revision of own argument for greater robustness.

- **Attractors/Barriers (AB) Framing**

"The Attractors/Barriers method guides the decision maker to view the features of the situation in terms of ways to facilitate or interfere with desired outcomes. In a complex system it is not possible to predict outcomes with any degree of consistency. As multiple agents (individuals, ideas, decisions etc.) constantly interact one with another the number of possible patterns that can form from the various interactions makes it impossible to predict. However, agent interaction takes place within barriers and around attractors, perhaps better understood as "attractors attract and barriers repel". The AB method provides an analytic approach to a complex problem by getting the participants to describe the situation not in terms of causality leading to predictable outcome, but instead to describe the nature and type of attractors and barriers that are in play" (Snowden & Klein, 2007). Through metaphor, the AB method allows user to describe situation efficiently at a higher level of abstraction from reality, by focusing on aspects of situation (attractors and barriers) that can be changed and are tangible. The AB method works best when describing situation of future uncertainty.

- **Future Backwards**

Originally developed as an alternative to scenario planning, this approach aims at extending the range of possibilities that people will consider. The process is fairly simple and can be run over several hours or 10-15 minutes depending on the consequence. The intention is to gather the maximum possible number of decision or "turning" points in the past and possible futures, thus emphasizing interventions or decisions (stepping backwards in time to current state and identifying turning points along the way).
The goal of this method is to extend the scanning range of the decision making group. Having people engage in hypothetical reasoning around a highly certain event (e.g. a future state that is presented as a given), they work more diligently and creatively than when dealing with highly uncertain future states. This is a benefit of prospective hindsight." (Snowden & Klein, 2007)

- **SA Calibration Exercise**

"Situation Awareness (SA) refers to people's understanding of the environment (what they see and perceive around them). Good SA provides a basis for sound decision making. If people's view of the world is inaccurate, their decisions will likely result in a suboptimal outcome. The same is true for teams: if they fail to establish and maintain a common understanding of the dynamic situation, they will not be able to execute the Course of Action smoothly and accomplish the mission. The challenge in building SA in a team is that if everyone sees the world the same then the team loses a diversity of viewpoints. But if everyone sees the world differently then common ground breaks down and coordination becomes difficult.

The SA Calibration Exercise provides participants with insight into how others view the situation. It helps them understand the subtle cues and environmental factors that affect others' actions and decisions. In order to obtain data, the exercises were interrupted and the following questions asked:

> 1. *What is the immediate goal of your team?* This question examines how well the objectives was understood and remembered. Often, team members only report the big goal and fail to report the immediate sub-goals
> 2. *What are you doing to support this goal?* Team members must understand both the goal and what they are supposed to be doing to support that goal.
> 3. *What are you concerned about?* This question helps uncover how participants are interpreting events in a threat situation. Some participants are worried about their ability to achieve the immediate goal while other team members may express a broader range of concerns.
> 4. *What is the current threat location, size, and intention?* This question served as a reality check on how each person had assessed the situation. This illustrates how participants understand the importance of maintaining a "big picture" view and avoiding tunnel vision
> 5. *What do you think the situation will look like in X time (time period depending on context) and why?* The responses to this question can facilitate a discussion about how different pictures of the future situation are affecting current execution.
>
> In addition to being an intervention, the SA calibration exercise is also a method of data collection, by providing experimenters with the ability to peer into an individual's cognitive sense-making processes and see how those individual processes were affecting the outcomes of the teams." (Snowden & Klein, 2007)

Along with the concept of critical thinking, sensemaking methods propose useful and concrete tools to help improve collective sensemaking through detection of weak signals, view exchange, legitimization of original approaches, and adoption of new perspectives. However, these methods would need further testing, especially in operational settings. Particularly, their actual benefits on sensemaking have to be demonstrated. Some of these methods may also be difficult to transpose in real situations, especially under time pressure, although there may be interesting with regard to training purposes.

The REACT method (aviation)

The REACT method was developed within the framework of the REACT project commissioned by the French Government Defense procurement agency ("Direction Générale de l'Armement", DGA). The project's aim was to define and assess a new method to support sensemaking in the face of unexpected events.
The REACT method can only be applied under specific circumstances. Hence, situations must involve the following characteristics:

- Dynamic and complex situations involving high risks
- Unexpected and threatening events
- Rare or unknown events, not covered by standard procedures and not immediately understood (data are incomplete or missing).
- Situations involving sensemaking and decision making of a team (collective reaction to the unexpected)
- Time pressure is high but not extreme (situations involving survival reflexes are out of the scope): there should be at least a few minutes available to react.

The REACT method is based on 6 principles:

1) **Collective vigilance to abnormal signals**
This means seeking actively and sharing all deviations from the expected/known, without trying to interpret or judge them in the first place.

2) **Collective acknowledgment that the situation is not understood anymore**
Human tendency to deny loss of control and over-optimism can stand in the way of successful "acknowledgment" of lack of understanding.

3) **Quick test.** Three questions are to be asked:
    1. Is there time available to make sense of the situation?
    2. Is the system safe? → Check that the system is safe, at least for the time needed to understand the situation and make a decision.
    3. Is it possible to find data to make sense of the situation?

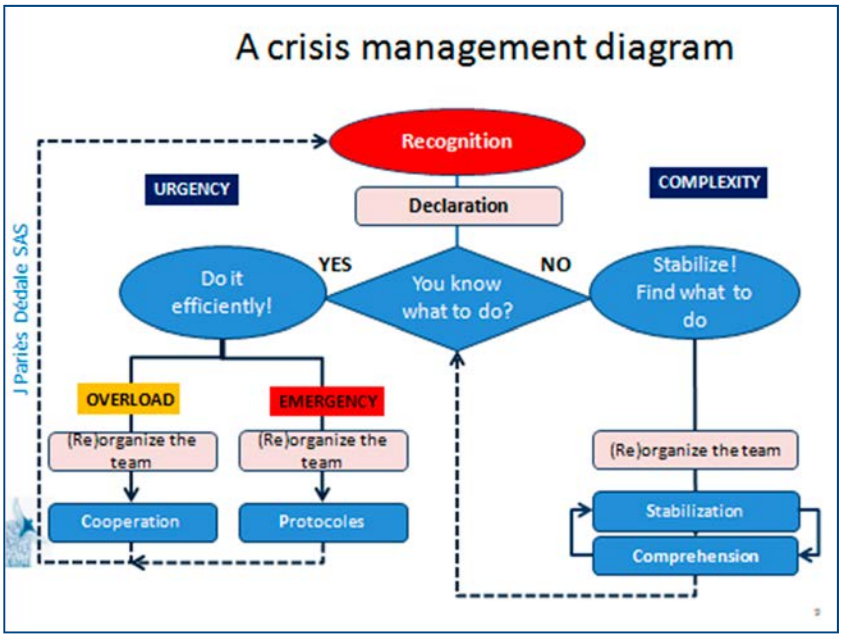
4) **Calling for external support**. Has the group the necessary skills to tackle the issue? If not, check if external skills are readily available. In other cases, keep in mind the team's skills limitations.

5) **Taking a more global view**: putting things into perspective to re-analyze the situation with fresh eyes. For this purpose, tasks need to be relocated among team members so that all or part of the team can detach themselves from the on-going action and get a general overview of the situation dynamic.

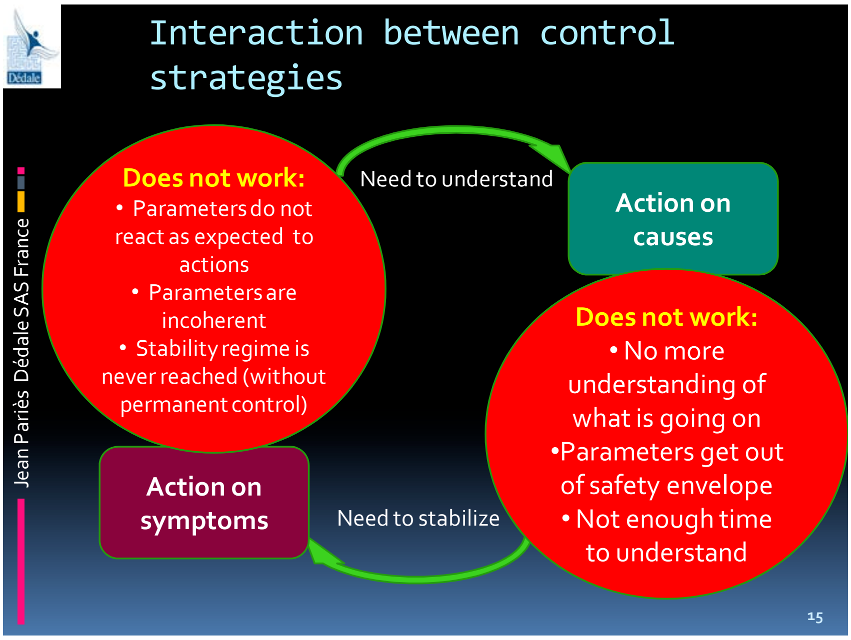
6) **Collective formulation of a well-argued explanation of the situation**.
    1. Summary of events along with context (when, who, how)
    2. Elaboration of alternatives/hypotheses without immediate judgment of their validity and consequences: use of the "crystal ball" technique, "Brainwriting" etc.
    3. Test of hypotheses, search of arguments and counter-arguments, selection of a plausible story.
    4. Critical assessment of selected story: check coherence against other known events and past experiences:
        i. Any uncertainties?
        ii. Any incomplete data?
        iii. Any inconsistencies?
    5. Final assessment of the situation, further developments expected.
    6. Collective decision making

The REACT method (Intensive Care Units)

In an unpublished research[11] to develop crisis management training for Intensive Care Units (ICU) staff, we have further elaborated the REACT method to better address the interaction between action and comprehension and the notion of "enacted sensemaking" described by Weick,1988): "*There is a delicate trade-off between dangerous action which produces understanding and safe inaction which produces confusion*" (Weick, 1988).
In order to provide ICU staff with the skills to efficiently manage this trade-off in order to maintain 'vital functions' at stake during emergency situations, we designed a simulator based training during which practitioners first receive a briefing about the effects of unexpected and/or stressing events on individual and collective performance, and are provided with generic strategies to faster recognize crises (loss of control threats) and better manage them. Then they experiment a series of three simulator sessions during which they try to implement the lessons taken from the briefing while confronted to tricky unexpected scenarios leading them to lose a proper understanding of what is going on. Each scenario is debriefed and the participants progress towards a better understanding of the effects of emergency situations and of the means to better manage them, with reference to a "crisis management diagram", building on the two main categories of crises described previously in this paper:



[11] REACT project, in collaboration with the Intensive Care Unit of the Geneva University Hospital (2012)



We also elaborated on the stabilization/comprehension loop, building on the dual control strategy commonly used by practitioners: the symptomatic strategy (acting on symptoms) and the etiological strategy (acting on understood causes):

6.2.4. Decision making support tools

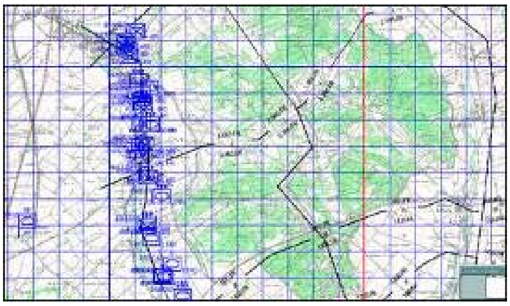
Another way to support decision making in the face of unexpected events is to provide decision makers with specific support tools.

Situation awareness support tools

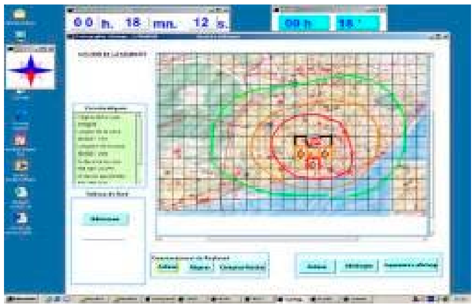
With regard to improving decision making process, situation awareness support tools are the most common type of tools. They correspond to information systems that offer a simplified, often coded representation of the on-going situation. The vast amount of data is filtered and synthesized in the form of graphs, diagrams, maps or tables. These schematic representations of the situation allow decision makers to overcome information overload stemming from human cognitive limitations, while also providing a basis for shared representation among team members.

There are two types of situation awareness tools:

- *Environment representation tools*
  Such tools are based on a map of the environment upon which are provided a set of data: resources, access roads, buildings, etc. Some of them allow simulating the physical consequences of a crisis trigger (e.g. spreading of a fire, flooded areas, or earthquake consequences).
  Such tools are particularly used to handle natural disasters (e.g. “UrbanRisk” software) or in the military (e.g. SIR regimental information system).



SIR system



UrbanRisk

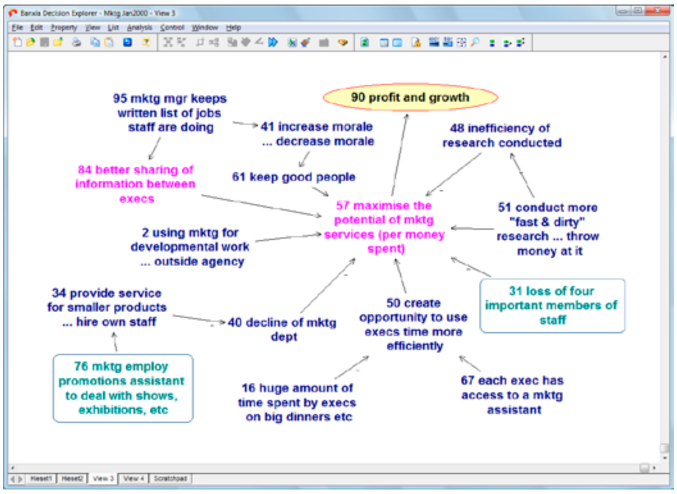
- *Organization representation tools*
  Managing the unexpected often consists in managing available resources of the organization. The more complex the organization, the more difficult to handle is the situation. This is why some tools are specifically dedicated to support better representation of the organization. One such tool was developed following the 9/11 attack to enhance coordination of New York emergency services: its interface displays an overview of units' organization and is updated in real-time.

The main advantage of situation awareness tools is they offer team members a way to share a common representation of the situation, thus promoting collective sensemaking and decision making. Most of those tools can be used in both crisis situations (real-time management) and training setting (simulation of incident cases). They can also be a useful mean to analyze retrospectively what happened and what led to a crisis situation (finding out causes through analysis of recorded variables).

However, situation awareness tools only achieve mere filtering and synthesizing of information without providing any actual reasoning aid. Even if they can simulate a great number of scenarios, they are limited to their specific framework which cannot actually accommodate unexpected situations. A study by Clegg et al (1997) showed that 80% to 90% of these information systems do not achieve their target objectives for which they were developed. This may be due to a lack of consideration for organizational factors, context, and users' cognitive model.

Cognitive maps

In order to support decision making, it is interesting to understand how individuals (or groups) structure their knowledge and use them to analyze a problem. Hence, the concept of "cognitive map" was developed to depict how a person defines a given problem. There are many different types of tools available for cognitive mapping. Rather than a general model of thinking, cognitive mapping is a visual representation of knowledge made up of concepts and relationships which help individuals understand a given situation (Weick & Bourgon, 1986). A cognitive map displays individual knowledge as well as collective knowledge ("collective map"). It is used to facilitate collective thought and decision making toward an issue, and can help picturing the consequences of an alternative in response to the issue.



An example of cognitive map

A cognitive map is a tool that allows depiction of mental representation of an individual or a group facing a problem. It generally comes in the form of a diagram with nodes and causal relationships. Creation of such maps is based on specific interviews which are then analyzed and organized to identify common elements among individual maps. Quantitative and qualitative analysis techniques are necessary to give meaning to the data.

Cognitive maps are used to:

- Analyze and structure information and knowledge in a group, by picturing information visually
- Model a complex phenomenon
- Support problem solving and decision making

Cognitive mapping stands out as an interesting analysis tool to support decision making in the event of unexpected situations (improvement of collective understanding of the situation and support for the development of alternative solutions). Nonetheless, some limitations need to be considered:

- Complex implementation, especially if time is limited. Creation of cognitive maps requires a lot of efforts.
- Limited size (otherwise the map becomes unreadable).
- Difficulties to organize information and identify relationships in some cases.

For these reasons, cognitive maps may be of limited use when confronted with unprecedented, unexpected situations involving high time pressure.

Decision Support System

Following the occurrence of several accidents in the military (shooting down of Iran Air 655 by USS Vincennes in 1988 and near-sinking of USS Stark in 1987), the U.S. Navy launched the TADMUS (Tactical Decision Making Under Stress) program. The project aimed at developing a decision support system (DSS) based on the naturalistic decision making model (Hutchins, Kelly & Morrison, 1996).
The DSS interface is made up of several modules to provide support throughout the successive stages of critical thinking.

The DSS interface

The DSS follows the principles of the critical thinking concept:

- Supporting situation representation and scenarios: the DSS provides a global vision of the situation with detailed information on each unit to support representation of situation and creation of scenarios. It also gives synthesized information, history and alerts to help overcome limitations of human cognition.
- Identifying whether the situation is familiar or abnormal: the DSS is able to compare the on-going situation to a pre-defined list of situations which allows easy and rapid detection of deviations.
- Assessing reliability of information: the DSS provides operators with a summary table to help assess reliability of data for each unit (data are labeled as "sure", "hypothetical", or "unknown").
- Assessing action plan: the DSS indicates in real-time which standard procedure is to be applied, step- by step, and as a function of mission objectives. Distance and acceptable time limits are also reminded before action.

The DSS provides officers with all information needed to implement critical thinking. It can be used for real-time crisis management or as support medium for training sessions on critical thinking.

Several studies have assessed the DSS tool on scenarios involving high levels of uncertainty. They highlighted a number of benefits in terms of decision making:

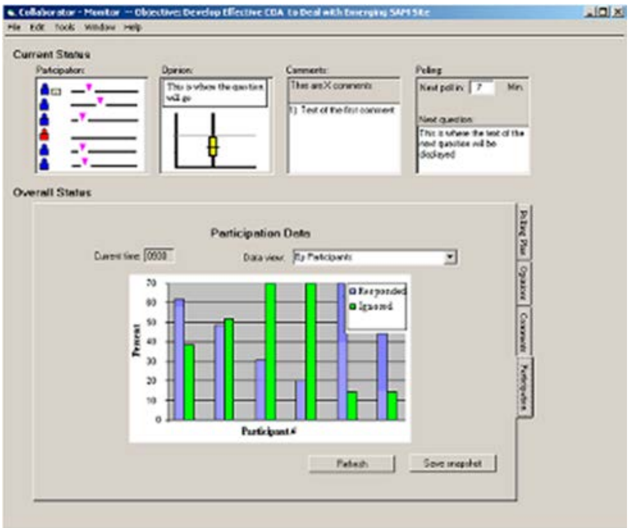
- Larger number of critical/suspicious situations detected
- Sooner detection of conflict risks
- Easier coordination between decision makers and operators
- Decreased number of clarification requests
- Faster decision making
- More appropriate solutions

Given the promising results, the same principle has been studied in the United States to develop such a decision support system tool for operational command centers (Office of Naval Research). It should be noted that the DSS has mainly been assessed in situations involving individual decision making. Further research should be directed to evaluate benefits on collective decision making.

Collaborative critical thinking tool

Further to the success of the critical thinking model, attempts were made to develop a similar reasoning method for decision making within a team. Collaborative decision making facilitates the production of alternative solutions, criticism, and questioning of scenarios and arguments through dialogue. To this end, the U.S. Navy developed a collective decision making support tool based on critical thinking: the "Collaborative Critical Thinking tool" (CCT tool).

The CCT tool requires each team member to rate anonymously their level of confidence or agreement upon a given issue (a scenario, a plan etc.). The aim is to compare points of view to make the best decision (Freeman & Hess, 2003). The underlying principle is that every member of the team has the same level of involvement in the process of collective decision making.



The CCT tool interface

The CCT tool involves a voting system that moves through several stages to come to decision making:

1) All team members rate anonymously the leader's proposal on a Likert scale (as a way to express their level of agreement).
2) The team leader gets access to the answers through the CCT tool's interface in the form of a graph, which quickly shows if a consensus has been reached or not within the team.
3) If everybody agrees, decision is approved and applied
   If there are profound disagreements within the team, the action plan should be questioned and discussed in order to reach consensus. Response times are displayed in order to foster quick decision making.

The CCT method requires submission of an initial proposal in order to start the voting process. Yet, forming this initial representation of the situation is precisely an issue in the face of unexpected events.

The CCT tool gets back over the concepts of data reliability assessment, scenarios questioning, alternative proposals and time management that are at the root of the original critical thinking concept. The CCT tool is one of the rare tools that address collective decision making. Further, it raises the issue of anonymous contributions in a group setting. Yet, the Collaborative Critical Thinking tool remains a prototype and has not really been formally assessed. One could thus question the feasibility of its implementation in situations involving high time pressure.

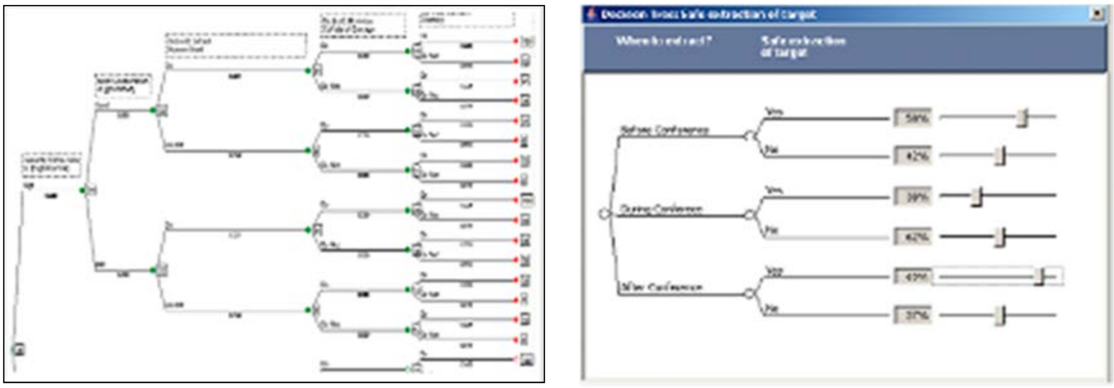
Tactical Group Decision Aiding System (TGDAS)

The Tactical Group Decision Aiding System (TGDAS) tool was initially created to improve collective decision making through computer analysis. For this purpose, the

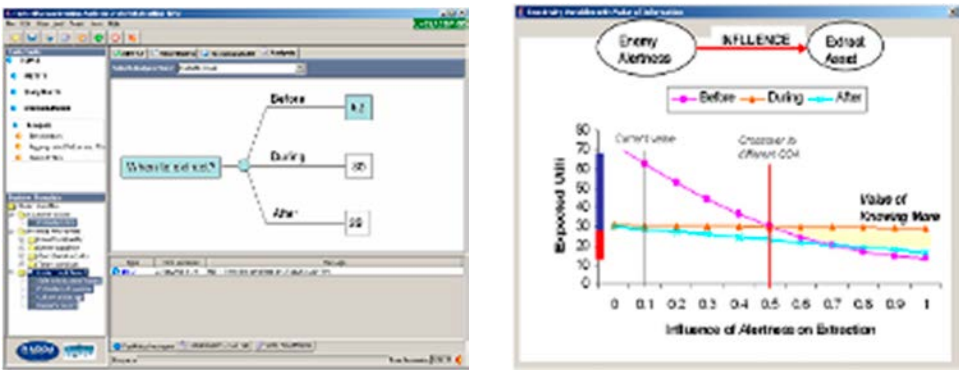
TGDAS combines principles of critical thinking with an analytical processing of data which can manage huge amount of information from a large team (Freedy, Cohen & Weltman, 2007). The TGDAS tool has been developed and implemented by the Defense Advanced Research Projects Agency within the “Collaborative Decision Support Projects” framework.

The method is based on:

- Creation of scenarios: each member of the team imagines a scenario based on data provided. The scenario is then implemented in a matrix.
- Sharing: from this matrix, the TGDAS tool proposes a decision model that displays all possible alternatives available to the team (use of an influence graph).
- Options assessment: users assess the relevance of each option which depends on the level of probability and priority assigned to each option.
- Selection of an action plan: the software calculates the best action plan and provides the corresponding decision tree.
- Critical analysis: the system identifies sensitive points (those who can result in major changes of the action plan) and brings them to the users’ attention so that the latter can compare them, criticize them and decide on the best option from a number of different dynamic graphs.



Screenshots of the TGDAS tool



Screenshots of the TGDAS tool

The TGDAS tool demonstrates good results on collective decision making and uncertainty removal. However, its implementation takes too long with regard to emergency situations under time pressure (creation of scenarios, assessment of each option etc.). Furthermore, the TGDAS tool assumes, in order to create initial scenarios, that the situation is well defined and shared by all, which is not the case facing the unexpected. Although it may not be used in real-time management of unexpected situations, the TGDAS tool can still be a useful medium for training in managing crisis situations.

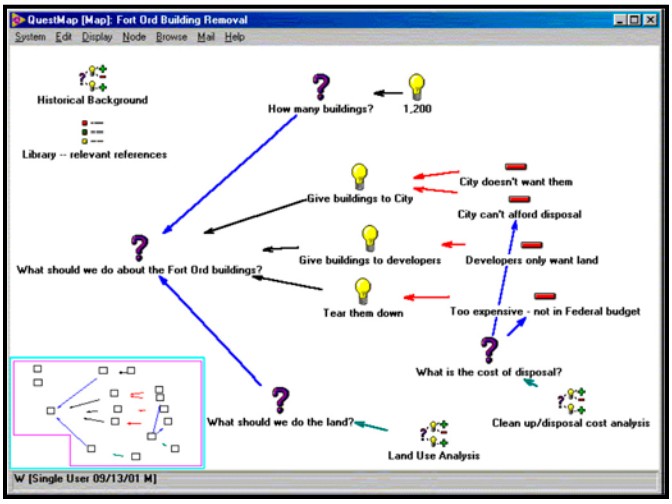
Structuring and visualization tools for sensemaking

As explained by Klein (2004), sensemaking is the process of fitting data into a frame and fitting a frame around the data. Hence, available data are compared, modified or re-organized to fit a particular and coherent frame of situation understanding. A frame is a structure which defines entities and relationships between these entities. It can take the form of a mental representation, a plan, a map, a story or a mental model (Hutton, Klein & Wiggins, 2008). Based on the data-frame theory of sensemaking, many tools have been developed to help decision makers structure and visualize available information and construct a frame.

Two main types of tools exist to support sensemaking:

- ***Argumentative tools***

  Argumentative tools assist in answering a question by creating an argument map focused on the question. They gather all available information with as much details as possible on a topic, and create pools as well as causal relationships among pieces of information. Reading and understanding of data become easier. Hence, argumentative tools provide an overview of possible solutions to a problem and compare those solutions. They were developed to allow collaborative construction of an argument map so that every member of the group can fill in his/her opinion and criticisms.



- ***Narrative tools***

  As demonstrated by Van de Rede (2007), building of a story complies with most characteristics of sensemaking. In this regard, narrative tools are able to support the sensemaking process by assisting decision makers in building a complete and plausible story from available data. Narrative tools can be used as a medium to guide the process of solving and organizing knowledge and reasoning by providing a chronological visual of the sequence of events (Soulier & Caussanel, 2002). Relationship types between events can also be defined in order to help understand the chain of events. Based on the visualization of both temporal aspects and arguments, users can assess the coherence of the story they have built. Visual representations also enable easier comparisons between different scenarios.

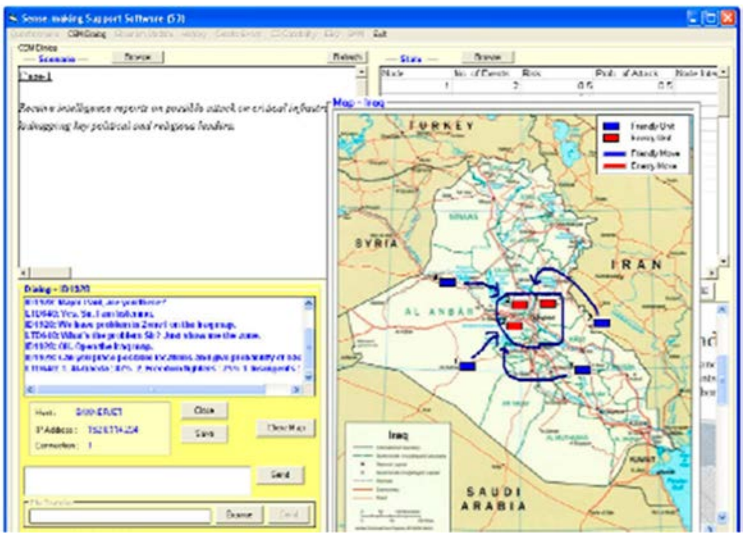
There are very few narrative tools available, as they are actually quite little-used. As an example, the AVERs software is used in criminal investigations (Braak, Vreeswijk & Prakken, 2007).

Visualization tools are interesting with regard to managing the unexpected. In the face of unexpected events, decision makers can methodically and collectively share their knowledge upon a common visual representation. Visualization tools assist decision makers in building a coherent reasoning with available data. However, such tools are mainly used in contexts that do not involve time pressure, as their implementation takes time indeed. Their actual benefits would also require further assessment. Yet, the principle of visualizing and representing information is of utmost interest with regard to the issue of managing the unexpected.

Sensemaking Support System

Based on the theory of sensemaking, the Army's Center of Battlefield Excellence in Human-Centric Command & Control Decision Making has developed a prototype collaborative tool which aims at improving sensemaking of a military decision-making group (Ntuen & Gwang-Myung, 2008). The Sensemaking Support System (or S3) is collaborative software to assist with preparation and mission monitoring, based on the sensemaking theory's principles. The objective is to support creation of individual representations of the situation while allowing sharing of these representations among team members. The S3 tool also promotes creativity and implementation of critical thinking.
The main functions of the S3 interface are as follows:

- Sharing tactical knowledge and exchanging expert views through a network dialogue system (verbal or written).
- Searching for more information through a search engine, an internet connection and access to data bases.
- Building and sharing different pictures of the situation (map, drawing, photography, text, diagram etc.)
- Allowing the team to submit action proposals or discuss proposed solutions.
- Assessing proposed actions through a common risk assessment table.
- Sharing a common representation of the situation by monitoring orders and actions.
- Getting access to the history of actions and information exchanged.



Screenshot of the Sensemaking Support System (S3)

The S3 software has been assessed only subjectively by users who had to rate benefits with regard to “sensemaking”, “situation awareness” and “situation understanding” issues. The results showed that the S3 tool can benefit users at once individually and collectively, while also saving time (Ntuen & Gwang-Myung, 2008). Further studies are needed to conduct objective assessment of the S3 tool and evaluate its actual benefits in operational settings.

7. The management of the unexpected in regulatory activities

Within the framework of this paper, it was initially planned to describe regulatory approaches related to the management of the unexpected in the following domains: Aviation, Nuclear Energy, Medical, Oil Industry, Seveso regulated industries. This ambition turned out to be out of reach within the available timeframe, due to the large existing differences in the regulatory frameworks, and the difficulty to access the relevant information: there is currently no standalone “chapter” addressing the management of the unexpected in those regulations. Regulatory provisions do exist to address the unexpected, as illustrated through the few examples given in this paper, but there are not necessarily labeled as such, and are scattered under many different headings. This state of affairs contributes to illustrate that regulators tend to think in terms of full control, and that they mainly see their role as making sure that the implementation of safety regulations by risk producers leads to an exhaustive anticipation of threats and the implementation of corresponding protections.

However, a discussion of “how can a regulator play its role concerning the management of the unexpected” has been conducted with four SSM senior managers, Heads of the following departments: Structural Integrity, Operations, Construction, and Emergency Response. This section summarizes the topics discussed.

SSM does **recognize** that unexpected events happen. They can be of external origin, such as earthquakes, tsunamis, heavy winds, loss of external power supply, flooding, high sea water levels, ice storms, or of internal origin, such as fires, unknown degradation mechanisms (“we don’t have a full knowledge of degradation mechanisms. The same mechanisms may act differently in different places”, e.g. Davis-Besse Vessel Head cracks discovered in 2010, revealing an unknown aggressivity of boric crystals against stainless steel), human errors (e.g. Forsmark 2006, total loss of external power indications, due to a mismatch between actual connections and documented connections).
Reducing uncertainty through knowledge collection, research, and operating experience is good, but it cannot be the only strategy: the remaining uncertainty associated with the risk model must be recognized and managed. “We need to be permanently aware that there are a lot of uncertainties”. The basic strategy for the unexpected in the nuclear domain is the **defense in depth** paradigm:

- Level 1: robust construction, sufficient design margins, robust and stable operation
- Level 2: surveillance, monitoring to control that the conditions are consistent with the design
- Level 3: safety systems to handle “things that happen”, transient conditions
- Level 4: accident procedures to take care of uncontrolled disturbances
- Level 4: evacuation of people

The strategy is good, but its implementation may not be: e.g. in the Fukushima case, the regulator did not push Tepco strongly enough to take into account possible higher tsunamis’ height in combination with a total loss of off-site electricity supply. There was a range for interpretation: level 1 and 4 defenses turned out to be undersized. From this perspective, Fukushima was also a man-made disaster. **Stress tests** are a way to reinforce the strategy and better address large uncertainties: design is based on best available knowledge, additional margins are taken, and “what if” is addressed. However, the focus of stress tests is on environmental and external aggressions, and on technical solutions.

The role of human operators in the management of severe accident situations is not yet covered by a stabilized philosophy. In normal situations, operators are only expected to adapt production to demand, while remaining within the safe operation envelope. If they get out of it, an automated reaction of the facilities will trigger a shutdown. In accidental situations, operators potentially have a larger role to play for safety. But different countries have different philosophies. In Sweden, during the first 30', everything should go automatic. But operators should be able to shut down the automatisms and do something else if they realize automation is going the wrong way. Normally this is not possible from the control room, only from the cabinet. In the US, shift supervisors have more autonomy, but there is less automation, and they can be taken to Court if they do it wrong. In Germany, the automation would go to the end.

In brief, there are two trends. One trend is to focus on the poor reliability of human operators: under stress, when information on the actual state of the installation is missing, or incorrect, or simply misinterpreted, they make wrong decisions. This trend consequently advocates fully automated responses: safety devices should automatically be triggered, and human intervention should not possible until the end of the automated sequence and the stabilization of the situation. A second trend is to consider that the operators must be able to interfere if they find that automation does not act in the direction needed by the situation.

In both cases, the critical issue is the reliability of the information on the status of the facilities. "You have to be sure that parameters show reality". One way to get such reliability in unexpected situations is that the reactor instrumentation and control system take into account the value of simplicity and robustness. Occasionally one more safety system is added to the current design and the PSA says safety has improved, but it does not take into account the increased complexity, the risk of interferences, of miscalculations. "We should go for simple design and simple passive safety systems". New reactors' design tends to be passive. From a regulator perspective, the development of requirements in this field would require the availability of metrics of complexity, and possibly metrics of novelty, as more uncertainty is associated with new (unproven) components, which is similar to more complexity. This would be a way to capture traditional empirical wisdom into requirements.

Robustness is difficult to assess as such. It adds up from different things such as redundancy, diversity, competence. **Diversity** is important. It is not favourable to reliability, but it is favorable to robustness, because it provides a protection against common mode failures. Robustness is more important than reliability. "After Fukushima we rewrote requirements. We asked for more and longer autonomy, more equipment. The tricky part is when you lose all indications. "We should require a diversity of equipment in the neighbourhood of a plant, through contracts with local entrepreneurs who provide equipment".

A similar discussion applies to **procedures**. "What we expect from operators should be regulated". Hence, "when something new happens, we write a procedure". "Operators in the control room are expected to stay within the procedures". But when something really new and unexpected happens, the procedure may be inappropriate. Hence the question is: when to leave a procedure? One key condition for sound behavior is experience. From this perspective, "we have a generation shift. The former generation attended the initial commissioning of the new plants, they were exposed to frequent anomalies and fixes, they have a better understanding of the potential problems and they have an experience of managing problems. New groups have not: they are very good at normal operations, but they are worse in the unexpected”.

Can a proper **training** compensate for this? “We don’t run bad disasters in simulators, we are afraid of giving them a wrong idea of what it would be. A good team in crisis may not be good in normal situations. Training is seen as problem solving, tools are to be used both in normal and exceptional situations”. Furthermore, the need for such a realistic training is not necessarily strongly felt. “Utilities anticipate accidents formally but actually they don’t believe it can happen to them, so they do the minimum”. “It would never happen here” is a common expression. “Fukushima was a very extreme situation; it cannot be compared to what can happen in Sweden”. We need a kit to train managers and operators for the management of the unexpected.

In complement of proactive, systematic safety analysis and research to fight uncertainty and randomness, there is also a need for a better use of randomness. “Following the discovery of cracks in the reactor vessels at Tihange 2 and Doel 3 nuclear power plants in Belgium in August and September 2012, one Swedish pressure vessel was stopped for inspection. It meant random discovery complementing proactive material degradation research”. “We need triggering factors”. Unexpected events must play this role, even when they are “weak signals”. “We also need to listen to whistle blowers. One Swiss professor working in Germany claimed that in certain circumstances there could be quick growing cracks in pressure vessels. We have to evaluate each of these prophecies”.

However, there will always be a trade-off between thoroughness and efficiency. There is no finite strategy fully efficient against the unexpected. “We need to reduce unnecessary burdens; we need a rationality to make risk informed decisions; we need to be aware of the uncertainty associated to the risk models, which makes fat distribution tails”. One difficult issue is that the society as a whole also has to recognize and accept the unexpected. Managing the unexpected cannot be achieved at any cost. “As a regulator I have the task to improve permanently safety. But I also have the task to match acceptable risk”. “In Sweden road safety faces a moose threat: fences cannot be put everywhere all along the roads, and people do not want to stop driving. So we try to find a rationality to make decisions; we use statistics and evaluate the potential “life cost” and the fences cost”. It is only one possible rationality, but it allows a consensus.

Can there be a shared rationality for nuclear accidents?”. For historical reasons, the acceptability of nuclear risks is a complex issue, very different from other risks. “Tsunamis do not question living on a coast of Japan, while they occasionally kill thousands of people. Why?” “As a regulator, we cannot establish this rationality. Regulators in Sweden must be fully opened to opinions. The regulations, the decisions we make go to our website and to the media. And the development of public opinion is itself… a high uncertainty process. After TMI and Chernobyl, there was a referendum in Sweden; the resulting decision was to close all plants after 2010. But we had a 50% nuclear and 50% hydraulic energy supply. We needed to secure electricity supply to paper mills and the like at a reasonable price. Eventually, in 1997 the decision was changed: two plants would be closed, and filters installed on the remaining ones”.

A further issue is the management of nuclear crisis situations. “An emergency is a situation in which some basic values are threatened. Any nuclear accident will be a crisis. We have three counties with a NPP. The county administration board will have to handle evacuation situations. There is currently no national plan to address this. One county will help the others. One problem is the risk of contradictory communications from different sources. We will increase our capability to handle it at a national level, to communicate in an understandable way to the population (and in English to international organizations)”.

Conclusion

Human beings are extremely efficient anticipative cognitive systems. Because they transcend routine and predetermined responses, unexpected events are destabilizing and threatening for human operators, who naturally ground their ability to respond on anticipation, expectations, and predetermined solutions. The high-risk industries, including nuclear power, have long worked hard to compensate for this weakness. The persistence of disasters which are literally made of "fundamental surprise", whose Fukushima is the most impressive recent example, shows that these efforts have not yet reached full success. One reason of this partial inefficiency may be that, ironically, the dominant strategy to manage the unexpected is to prevent the unexpected – to try and extend the ‘predetermination envelope’, to reduce the ‘domain of the unexpected’ through a more intensive and extensive anticipation. In other words, the strategy is to do more of what is already done, rather than learning to really cope with the unexpected, i.e. improving the ability of our organisations to manage the unexpected. However, a better understanding of the challenges posed by the unexpected to Human cognition, to teams and cooperation, and to organizations, would allow to develop complementary skills and tools to better handle unexpected situations.

In this note we have reviewed a sample of the available knowledge on the issue, as well as a sample of available techniques to improve man’s ability to cope with the unexpected. We have seen that a primary condition to better cope with the unexpected is to recognize it, then to develop resilience features, a compound of toughness and flexibility.

This applies to the design of organizations and socio-technical systems. This design should provide not only for the “requisite imagination” and anticipation of possible situations, for the predetermination of appropriate responses, but also for the diversity of resources, tools and competences, for the reorganisation capabilities, the flexibility of structures and role distribution, for the decision making capacity and reactivity, for the robustness of processes through back-ups, redundancies, vicariance, stocks, buffers, slack, needed when facing the unexpected.

This also applies to real time reactions to the unexpected, at both individual and team level. Operators should be trained, not only to implement predefined specific “emergency” responses, but also to quickly recognize a loss of control, to implement generic, high level strategies based on an efficient sense-making process, to assess the situation and make decisions under stress and uncertainty, to cut one’s losses and make “sacrificing decisions”, to maintain team coherence.

Such a perspective represents a real paradigm shift. In the prevailing vision of safety management, uncertainty is the enemy, and we seek to eradicate it through anticipation and predetermination. But this strategy generates a vicious cycle of predetermination and vulnerability, more predetermination generating more vulnerability, which requires more predetermination, and finally “robust yet brittle” systems, unable to handle disturbances outside their envelope of designed-for contingencies. In the challenger approach, we recognize that we are immerged in uncertainty: we live with it, we have evolved with it as living beings, developing cognitive and social skills to handle the associated unpredictability. We seek to better understand these abilities and augment their power in order to engineer resilience into our systems and handle variability.

However, such a perspective change would obviously be a challenge for regulators. It is much easier to regulate and monitor activities with reference to what is known and understood than with reference to the unknown and to uncertainty. “Bunker” based strategies can only do part of the job of managing the unexpected, and only apply to the physical components of the system. Other “resilient” features, such as diversity, flexibility, adaptability, vicariance, have been identified by recent research, as described in this note. Unfortunately, they are more abstract, more difficult to formalize, less compatible with public expectations than traditional reliability requirements. It looks like there is some work ahead –or as the French say, *du pain sur la planche* - for regulators.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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