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# Decisions Management during Wildland Fires: Accidents Viewed as a Spatiotemporal Inadequacy

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**Abstract**

Extreme situations as wildland fires are a source of stress and pressure. In such events, decision-makers and incident commanders need to address a specific problem: how to manage time and resources to make meaningful decisions? Current models of accidents that exist to explain and manage catastrophes and disasters are inadequate and insufficient to deal with resources and time pressure due to uncertainty within a complex organization. Current incident response structures are incompetent and impotent to handle effectively a dynamic evolution of space and time in order to bring a situation back to stability adequately.

***Keywords:*** Accidental state; Systems; Chaos theory.

## 1. Introduction

Incident response structures in complex, pressing situations creates unusual challenges for firefighters when time and resources are constrained and the consequences of failure are severe.

Hazards and threats are high, space is limited and time is insufficient, both for firefighters to take action and for the population whose lives and properties they seek to defend. As social organizations become more interdependent with physical and technical systems, the range of possible interactions among people and organizations, and the context in which they function rises, and the number of factors that influences potential actions and outcomes in constructive or destructive ways also increases. Subsequently, response to wildland fires tend to become an emerging, large-scale, sociotechnical system of people and organization, that necessarily need to coordinate their actions in a hazardous spatiotemporal environment.

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However, as verified in the Yarnell Hill Fire of June 30, 2013 [13], with its devastating loss of the field firefighting unit, the Granite Mountain Inter-agency Hotshot Crew, the spatiotemporal constraint of these events may exceed the organizational capacity of the emerging response system and seems to be in-adequate to face a fast-moving wildland fire [16].

This research focuses on the dynamic process be-tween people and organizations during the June 30, 2013 Yarnell hill fire to identify where the complex coordination failed. In addition, it explores how our approach to wildland fire management could be improved to enable response systems to better apprehend the parameters of time and space.

Decision making in fire management has been studied by many scholars [13, 15, 27], each contributing perceptive in-sights to this extraordinarily difficult task.

Our analysis focuses on the degradation between the different levels of decision-making in the response system to study how individuals lose or maintain their capacity for shared operations.

The role of each actor in the system is to maintain de-tailed knowledge of each of its functions in order to provide global support to all operations and at the same time to keep a clear vision on his own performance in the functioning of the whole system's response. This function can only be maintained through adequate representation of the space-time in which operates the system and actors. Such a task is cognitively challenging for individuals.

Firefighting is an activity extremely demanding to all stakeholders. The physical conditions are demanding, with an often hilly terrain, high and dry temperatures and a changing wind.

Therefore, the ability to adapt to the dynamic evolution of spatial and temporal conditions is fundamental to effective performance at all levels of the system.

Given the increased frequency of extreme weather and the increase in the cost of large-scale mobilization, socio-technical systems should now better take into account the evolution of their space of action but also the management of their time allotted to them to fulfill their task of control during extreme events.

### *1.1. Process, structure, function in context of firefighting*

Understanding an incident response structure requires to understand structure, function and a process at a given time [11]. These three concepts represent the three elements which, in a given space, form a whole.

The structure, function, process and context allow defining and understanding a space-time system:

- The structure defines elements and their relationships within a given space-time.
- The function represents the results or effects from a given space-time;

- The process explicitly defines the sequence of activities and how the results are produced within a given space-time.

Finally, the context defines the unique space in which the system is located at a given time. Thus, it is commonly accepted that to understand a system, it is necessary to understand its structure, where the predominance of the study of the structure in classical science. According to Ackoff, a given structure can perform several functions within the same space [Ackoff, 1971]. For example, the structure of a firefighting organization can produce safety functions in a global approach to performance improvement. Different structures can also produce a given function (Figure 1).

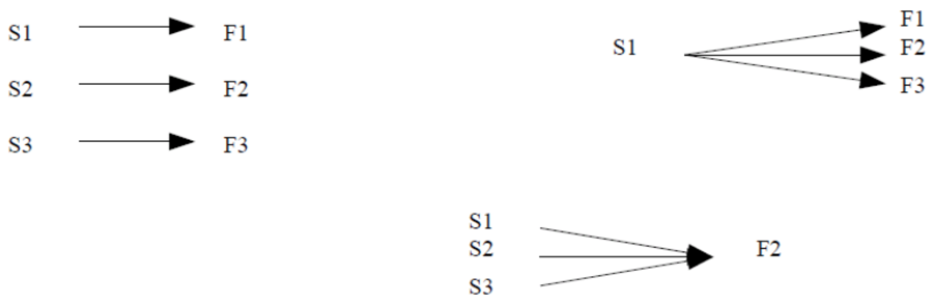


**Figure 1:** Relationship between the structure and the function. Adapted from [11].

The classical notion of causation, where the cause is the necessary and sufficient condition for the appearance of its effect, proves its inadequacy to ex-plain this phenomenon. Indeed, the production of different functions by a simple structure within a same space-time can be explained by the coexistence of different processes in the same structure, which pro-duce different functions at the same time.

However, when several functions exist for a given structure (firefighting organization) in a given space-time and when the processes within this structure be-come known, then structure and functions allow the understanding of the whole organization. Structure, function and process within a space-time form inter-dependent variables collective and exclusive. Together, these four concepts define a system or make its behavior understandable.

The simultaneous presence of interrelated variables leads to a circular relationship, where each variable and component of a firefighting organization co-produced the others and is co-produced by others [6, 7, 8]. Asserting that these variables form the basis would remain however vague insofar as each of them can exist without the presence of others; they must evolve within a shared space-time. A common mistake is to not look at the system as a whole. The holistic approach seeks instead to understand each variable in its relationship with others, in a given space. Therefore, in a systemic vision, these essential characteristics contribute to under-standing the accident.

**2. The systemic of the accident and the accidental state**

In a holistic vision of a system, it is therefore possible to identify '3 + 1' characteristics to define the system.

These "3 + 1" characteristics have also the ability to describe a systemic accident.

A complex system is a dynamic system whose behavior changes over time. This behavior is the result of controls within the system and may cause new configurations and new features, or even a dynamic that could lead the system to a hazardous state, some-times up to an accidental state. Indeed, the evolution of the characteristics of a system affects the function, the structure and processes. However, these three dimensions have the ability to define a behavior and therefore a state in a given space-time. For a system, it is possible to define an "accidental state" of a system as "the result of the migration of its systemic characteristics in a given space-time resulting in damage or losses. The accidental state can be explained via degradation of the processes, structure and function” [12].

This migration can be immediate or slow and start at any level of a system or a complex organization. Accident is an emerging phenomenon in a dynamic system, and it is difficult to see to understand an accident without understanding its dynamics. The purpose of the following paragraph is to present the concept of accidental state with regard to the theory of systems.

### *2.1. The accidental state*

The concept of 'accidental state' is directly derived from the theory of systems and the dynamics of the systems. An accidental state is considered to be the result of an accidental phenomenon resulting in a new space-time configuration characterized by a transition phase of its processes, structure or functions, in a given space-time resulting in a degradation of the system. In the case of an accidental state, the system is in an excited state due to internal and/or external disturbances (typically a wildland fire).

The accident is therefore an emerging dynamic phenomenon within a system and characterized by in-adequate responses (feedback) that faced with disruption affecting the oscillatory equilibrium of a system, and which can lead to damage and/or losses. This transition (degradation) of a space-time can independently reach processes, structure and function of the system having an impact on these three characteristics due to their interdependence and their interactions. That is why, in a given space-time, the degradation of a process has an impact on the entire system and affects both its structure and its function.

Socio-technical systems are always dynamic and non-linear [9]; however, in the interests of clarity, it seems easier to illustrate the notion of accidental state by adopting an integrated approach.

As noted above, within a system, process, structure and function are linked (figure 1). Thus, in a systemic process, any change — for example inadequate control— action, induces a change in the structure of the system (figure 1) and therefore its behavior. This change in behavior so alters the objective of the system and its function if no answer is provided in time by the system (figure 1). Conversely, any variation (performance) in the response sounds on the structure and the hierarchy of the system, resulting in a change of control actions and therefore a variation (performance) in the process [5]. Any disturbance of the system thus causes an oscillatory effect on the system with different consequences. Hence, small amplitude disturbances have only a limited impact and induce a linear response of low amplitude on the part of the system.

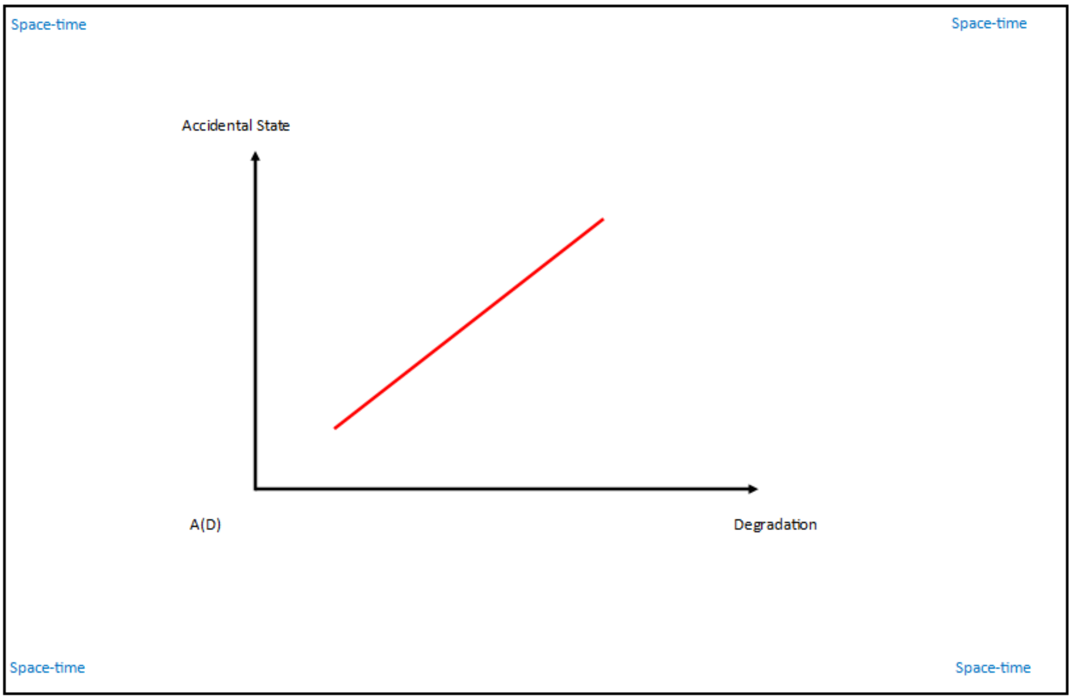


**Figure 2:** Linear (unanswered) representation of the accidental state of the system on the basis of its degradation. Adapted from [12].

It is therefore possible to represent these variations as well thru a processual vision, as well as structural or functional. If no answer or no control is made on the part of the top-level at a level being degraded, system migrates to a dangerous state, or even to its disintegration. This response should notably result in control action of the higher level on the concerned level in response to the information transmitted by the lower levels. This phenomenon is likely to spread to the highest level of the system, resulting in a migration of the entire system to a dangerous state — it is the complete integrity of the system which is at stake. In pursuing our linear reasoning for the sake of simplicity, the accidental State of a system depends on directly degradation of the same system in a given space-time (Figure 2).

It is therefore possible to define three different types of accidental state on the basis of the migration process: If changes in the process are the source of a migration of the system to a dangerous state, that state is called 'accidental state by processes' or 'migration by processes "; If migration due to a change in the level of the structure, this state is called 'status' accidental structural or "structural migration." Finally, migration due to a change in the function defines the 'functional accidental state' or 'functional migration. Within this framework, when there is no response, the migration of the process is such that the system enters an accidental state, leading inevitably to a destruction of the system by processes. This destruction could be followed by a migration of the structure and the function to an accidental state even leading to a complete destruction of the system. This evolution, shown in figure 3, can also be explained by strong disturbance causes the system to emerge from its state of rest taking it to an excited state and therefore accidental to finally move in a state of recovery before returning over time to a state of rest. These disturbances can be spread throughout the chain of command, they are base, top, inside or outside a space-time.

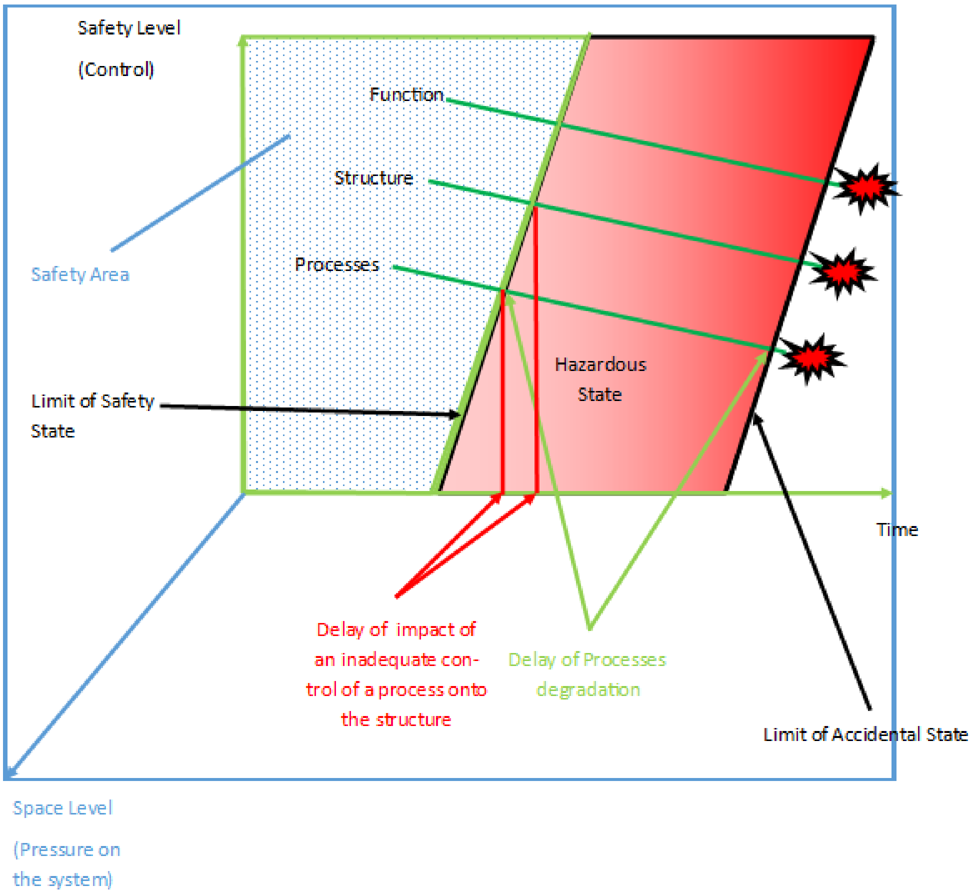


**Figure 3:** Linear representation of the accidental State due to migration by a system processes complex in a given context. Adapted from [12].

Figure 3 shows, among other things, the time constraint for degradation in this simplistic linear representation. These degradation time — and therefore migration of an incident response to the dangerous state — highlights a deferred structure then the function entries into a dangerous state, or even in an accidental state. The migration of all the characteristics of an incident response is progressive if no answer (control or adequate feedback) or supplied to the system within an adequate timeframe. Indeed, the three types of migrations are never simultaneously, except if a disruption (internal or external) affects the response in its entirety.

Naturally, several configurations may exist depending on whether this migration affects the structure or function. These delays (time variation in flows) are of a crucial importance in the prevention of accidents within complex systems and the management of the inadequate control actions during an extreme event. Indeed, more a complex system is slow to provide a response to an inadequate action, more the propensity is strong to migrate to a hazardous state. In general, time has a strong influence on the overall behavior of an incident response and modification of the duration of time might have an impact on the global response — for example, the response time of the system facing a disruption (internal or external). Thus, a delay is source of hazards by creating instability and oscillations in a given space-time. Ubiquitous [26], the deadlines are at the origin of time taking to measure or pass information, or to make a decision. Both may be that informational material.

It is thereore possible to define "a safe space-time state" as the state of the incident response for which its features lie in the area of safety, so out of any hazardous and, a fortiori, of any accidental situation. In a system, the complex management of accidental states is translated into management of actions at the level of processes, the structure and the function of the system.

In any socio-technical system, an accident is non-linear, and the result of a phenomenon in which the reaction is disproportionate to the action [25]. However, this nonlinearity makes any accidental prediction extremely difficult: in a non-linear system, errors are increasing rapidly indeed and un-certainty in the current state of a system does void any prediction of its state beyond a certain period of time and space. It is this property of nonlinearity in the system which allows producing emerging structures (adequate incident response) and generating a dynamic within a system. A non-linear system has no fixed point for balance point: its balance is a series of states that the system navigates to preserve its characteristics (process, structure, function) evolving constantly. The accidental state belongs to these systemic states.

Thus, it is continuing unrest and instability in the heart of this system, disorder and variation which produce order and conservation. In any dynamic system, the studied structure at a given time is produced by dynamics of the system, resulting in positive interactions (explosive loops) or negative (negative loops). In an incident response, with strong linkages, exist dynamic mechanisms capable to self-regulate in order to shape a stable and non-accidental space of evolution. This stability (or this feeling of safety) can persist long enough to seem constant. Then, due to a small change, feedback loops are likely to disorganize and even jump rapidly to another steady state.

This is why the system migration to an accidental state represented in figure 3 will differ, in the case of socio-technical systems, because of these feedbacks over time: migration loses its linear nature, and the incident commander is then indeed confronted with migration of the response in its entirety. Thus, the study of accident phenomenon of a nonlinear dynamic system is not exclusively done through an understanding of interactions between elements but also through the understanding of the properties of interaction between the elements (time, rhythm, frequency... among ac-tors: firefighters, aircrafts, jurisdictions…).

Consequently, the accidental state of a nonlinear dynamic incident response requires to understand the structure with emergent properties resulting from internal interactions under the influence of time with its own space. These emergent properties are those of the function of the system. Thus, in non-linear such as socio-technical systems dynamic systems, it is important to understand the structure of the system but to confine it. This approach of structural understanding passes the constitution of "models of systemic accident", and the analysis of its safety – emergent property resulting from the interaction of elements among them.

### 3. Toward a first model of “chaotic” accident

The analysis of the socio-technical systems strives to take into consideration their systemic properties and shows how a system can self-organize to maintain structural stability when it is far from equilibrium unless an outside force acts on it [Prigogine, 1979]. This complex behavior is non-linear and the links between causes and effects can be identified [3]. The positive feedbacks of complex systems are generating development and emerge the "arrow of time" [21, 22]; they should therefore be included in the screening process. Positive feedback cycles amplify the effects of disturbances (phenomenon of autocatalysis) increasing the amplitude of fluctuations. What are these positive feedbacks which put the system far from equilibrium and that allow to characterize resonances and to evolve.

Ilya Prigogine got the award of the Nobel Prize in chemistry in 1977 for his work on dissipative systems and on the concept of "time's arrow" [21]. A dissipative system imports energy and/or information from its environmental space that it dissipates, causing readjustments characterized by the emergence of the "arrow of time" and the formation of new structures that do not exist in stable equilibrium. Unlike a dissipative system, a stable steady-state system reorganizes, but releases only energy without absorbing and tends towards an attractor says "endpoint" [23, 24]. The most representative example is the ball which, placed at the bottom of a bowl, reaches a fixed position after releasing its energy.

From dissipative structures emerges a process of self-organization by a readjustment of the parameters of space and the emergence of the "arrow of time" characteristic of irreversible processes and evolution [23, 24].

The phenomenon of self-organization modifies the incident structure of the system without the intervention of an external force pushing it on a trajectory of a new attractor representing a new organized State. Specifically, fluctuations are to migrate the system to a basin of attraction to another basin of attraction. This passage between one basin to another is spontaneous and is due to fluctuations in conditions of instability without external intervention. Self-organization should be distinguished from the phenomenon of selection, which means the completion of a choice between different states of stability and thus states in competition, due to an external force on the system pressure. Self-organization is a new emerging space, an order of non-equilibrium [3]. The system can then display emergent properties and new emerging space-time structures sensitive to the values of the control parameters.

This new dissipative structure emerging by self-organization is an unstable structure that can be easily dissolved due to a change in the values of the control parameters. There is a mismatch between the new structure and control parameters. A dissipative structure remains so fragile, contrary to a steady-state structure. Faced with these findings, systemic accident models show their limitations in their efforts to study and analysis of a system far from equilibrium. A sociotechnical system is never in a continuous stable state and is even far from equilibrium. Therefore, such a system is a dissipative system [21] or adaptive with a capacity of self-organization and self-reproduction allowing it to change its space structure and to maintain the balance by dissipation (management) flow (matter, energy, information) over time.

Then, it is legitimate to ask if the accident is not the result of a spontaneous phenomenon of self-organization resulting as the 'passage' or a 'bifurcation' of a basin of attraction to another, resulting from a phenomenon of autocatalysis (positive feedback) [22]. The choice to characterize the 'incident' or 'disaster' accident would depend on the coupling between two basins of attraction, i.e. the differentiation and the connection between two basins of attraction (figure 4). A strong-coupling (a strong connection) would cause a phenomenon of 'incident', reversible, and then a change of basin simply because a strong-coupling allows a more 'soft' passage between two basins.

Suppose that A (located in A basin/space) and B (located in B basin/space) are two different systems including a crossing (a junction, an accident) from A to B with many elements in common. More the linkage (connection) is strong between these two systems of different spaces, more the number of elements in common is great and less passing (the bifurcation, the accident) from space A to space B to cause changes (of damage) due to a low differentiation [12].

Conversely, more the bandwidth is low between two systems of two different spaces, more the number of elements in common is low and more the bifurcation between space A and space B to cause changes (of damage) due to a strong differentiation. A low connection would cause a catastrophic, irreversible, phenomenon due to a forced passage into a space with that little "correspondence" with the space of origin.

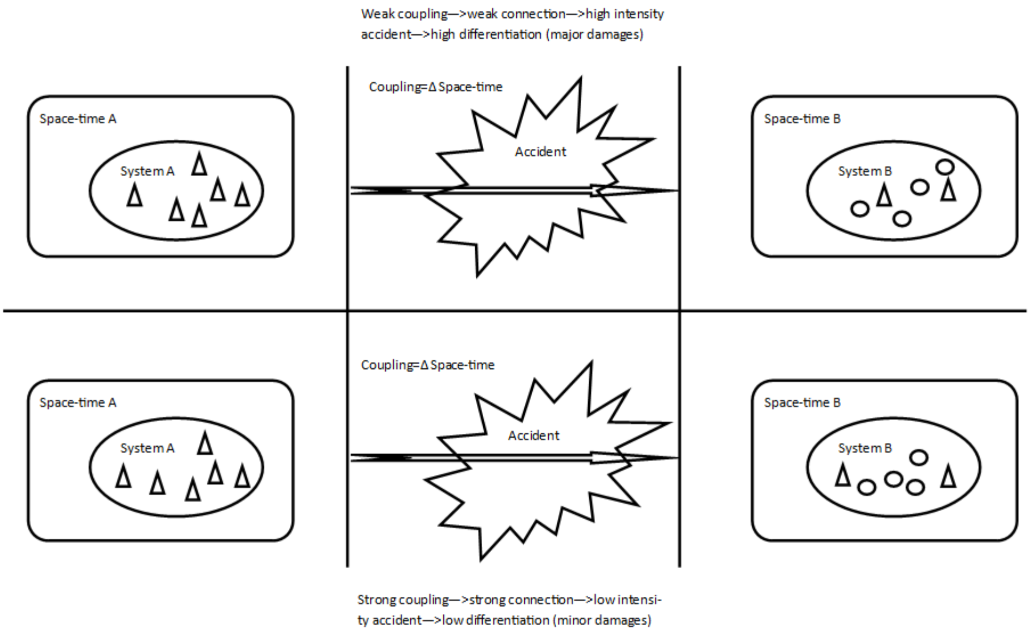


**Figure 4:** Linear representation of the accidental State due to migration by a system processes complex in a given context. Adapted from [12].

It is possible to propose a cycle of evolution of a dynamical system (figure 37), such as a sociotechnical system, taking into account disturbances and allowing it to maintain a state of balance despite fluctuations, or even changes in attractors, through bifurcations.

This cycle is based on several theories: theory of systems and control, the chaos theory, complexity theory and the theory of dissipative structures; It allows to lay the foundations of a model of chaotic accident.

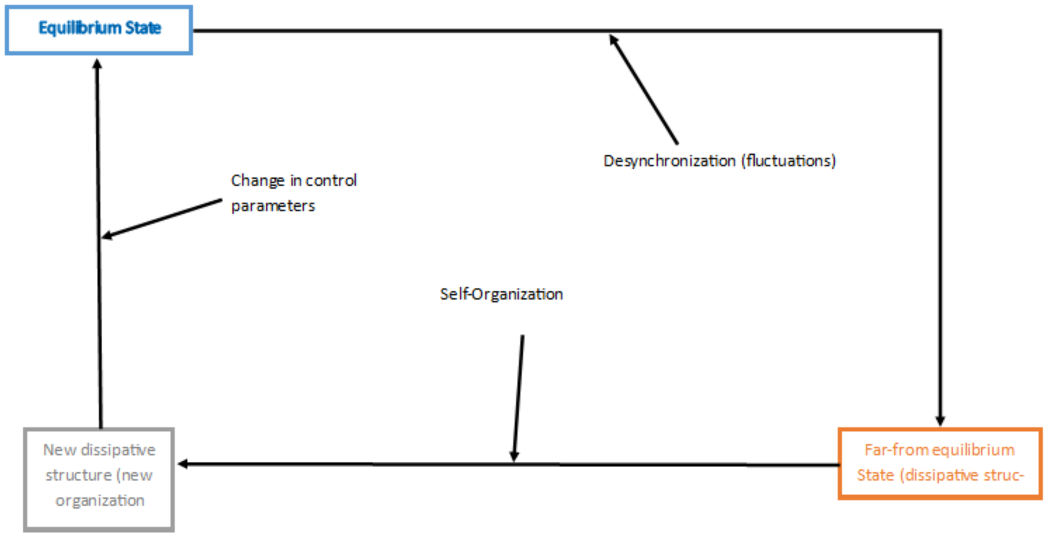


**Figure 5:** Response of a sync system Cycle. Adapted from [12].

By fluctuations, a system can be found in a state of balance stable, complex or chaotic. This evolution depends on the level of control and synchronization. It is in a state of complexity if it can create new spaces and create emergent properties (such as safety). Complexity results in a state change resulting from internal instability and/or external action on the system. The dynamics of a complex system is therefore characterized by trajectories sensitive to internal and external disturbances [3].

The fundamental objective of one such cycle is to avoid a 'chronic' desynchronization between a system and environment, pushing the system to its limit of prediction/understanding (corresponding to a 'Lyapunov time' positive and synonymous with impossible predictions and strong uncertainties [24]) and lay it, in the absence of adequate controls, to a new space of attraction through an accident (see figure 4).

Therefore, socio-technical systems are inherently complex systems, in a state of unstable equilibrium, may present a high level of safety. Indeed, the fact that a system is in an unstable equilibrium is not synonymous with safety. Meanwhile, a purely technical system, may be in a state of stable, complex, or even chaotic state [14].

**4. The phenomenon ‘Accident’ in a firefighting system**

The concept of accidental state in a system was previously presented. This definition requires some amendments in the case of a sociotechnical system since its relations are nonlinear [17, 18]. The accident is an irreversible and unpredictable event due a lack of appropriate response, following a reorganization not controlled in a given context and that can lead to damage and loss [12]. In other words, the accident is therefore a phenomenon of collision, breaking symmetry, bifurcation or transition from one system to another, caused by a lack of adequate response following a reorganization that is not controlled in a given space-time. The analogy is apparent between these two definitions; however, it must not hide certain disparities. The first is that an accidental state of a dynamic system can be integrated, a step, an event at the end of chain, a state of a system over time. This state is characterized in the spirit of individuals by the outcome of the occurrence of a risk — for example, a terrorist attack (the risk) can cause casualties or damage. This state of degradation characterizes the 'image' that you can have of a situation resulting from the occurrence of a risk. As part of a "chaotic" accident vision, the latter is no longer an end in itself or a state of the system at a given time, but a "symmetry breaking" generating its own arrow of time.

The chaotic accident can be defined as an irreversible (a change with its arrow of time) and unpredictable phenomenon due to a loss of control of the system in a given space-time. The 'accidental phenomenon' is spontaneous and realized that during a chaotic behavior of a dissipative structure of a sociotechnical system (directly dependent on its structure) toward a 'new' asymmetrical system. This "passage" of a system S1 to S2 system translates the accident for which (D) damages and losses are different (S1 - S2). A priori, for damages and losses, this difference remains always positive until the re-establishment of a state of equilibrium of the S2 system and can become negative as part of a process of return of experience or an organizational learning approach.

Indeed, the goal of a return of experience is a structural reorganization to emerge, through adequate controls, a synchronization of a sociotechnical system with its environment. Steady-state results from adequate controls in a given space-time (figure 5). This time recovery and application of adequate controls corresponds to the notion of 'crisis' during which a (still fragile) dissipative structure takes into account the context and dispels new appropriate information to the level of its structure to define adequate controls which will stabilize the structure by evacuation of entropy. The 'crisis' time is the time required for the structure to dissipate an updated flow (information, material, energy) leading to equilibrium. During a 'crisis', as long as the system does not find a steady state, other accidents can occur.

The accident must be distinguished from a simple organizational change by the "unpredictable" nature inherent by nature. An organizational change in a sociotechnical system can be irreversible but remains predictable.

The accident can therefore be described as an event or an irreversible and unpredictable phenome-non, even as an irreversible and unpredictable change of a sociotechnical system with regard to its environment, due to a lack of appropriate response to the level of its structure.

It translates a bifurcation of a 'safe' phase space to a new phase space ('safe' or 'un-safe'), inducing a symmetry breaking. However, the accident phenomenon emerged spontaneously from a bifurcation, which must not be seen as hopelessly leading to losses or damage but as force a response from the system in order to avoid any loss or simply evolve or develop.

The accident, in chaos theory, should not be routinely seen in terms of loss or damage, but as a 'need' for a system to equilibrate and ending 'in tune' with its environment and through processes of self-organization to maintain a state of equilibrium. It may seem original, even hazardous, to see the accident as a "need" but it is also capital to remind that this need remains independent of any social desire and it is always irreversible and unpredictable (Table 1).

**Table 1:** Qualification of a phenomenon based on its characters of predictable and reversible. Adapted from [12].

| **Phenomenom** | **Irreversible** | **Reversible** |
|---|---|---|
| **Unpredictible** | Accident | Incident |
| **Predictible** | Imperious | Crisis |

The dual character of irreversibility and unpredictability defines what an 'accident ' is: predictable phenomenon and irreversible consequences that lead to a pressing and irresistible phenomenon that is defined as "‘imperious’". An ‘imperious’ phenomenon prevents any system to achieve its goal; the system is out of control, resulting in damage and losses on its structure, preventing it from performing its function in a given space-time frame. This type of phenomenon can lead either to a phenomenon called 'crisis', or "accidents." This dynamic is due to the nonlinearity and unpredictability of a sociotechnical system.

Something unpredictable but whose consequences are reversible and do not lead to a loss of control is called "incident". Therefore, the ability of a system to produce an appropriate response in a given space-time forms the boundary between the reversibility and irreversibility of a phenomenon. The series of phenomena 'accident', ‘imperious’ and 'crisis' describes a space or an area of loss of control (a space out of control within the meaning of the chaos theory) does not allow to maintain the safety and may prevent it from completing its objective.

The 'incident' phenomenon is located in a space or a preservation area of control (controllable space within the meaning of the chaos theory) for a continuation of the system under control to serve a purpose. It is possible to define a control zone as a section of the space in which the system is "safe".

The accident phenomenon is a bifurcation leading a system to the confrontation with a reality requiring an adapted answer to keep it under control. Any inadequate response leads to an ‘imperious’ phenomenon. A sociotechnical system is then referred to as adaptive when it is able to integrate its dissipative structure level through a new flow (information, energy or material) to provide an adequate response during an event towards incident phenomena.

Over this qualification of different phenomena, it is interesting to note that an accident characterized a bifurcation from one 'safe' phase space to another due to a chaotic behavior. The 'accident' phenomenon is never directly the source of damage and losses unlike an ‘imperious’ phenomenon. The accident considered change of space highlights the need for the system to find a state of equilibrium in a given and sometimes turbulent space-time by integrating within a dissipative structure a new stream allowing it to effectively discharge its entropy.

An incident response willing to deal with the ‘imperious’ phenomenon ought to be able to cross the border between irreversibility and reversibility making it a complex adaptive system or not. In this perspective, the 'accident' phenomenon is never called "major" or "catastrophic" because the accident is only a breaking of symmetry. In this context it is the ‘imperious’ phenomenon that can be described as major or catastrophic.

The incident response whose structure is dissipative tries to maintain a “safe” space (or section) by releasing entropy via rearranging. When a threshold is reached then a bifurcation takes place leading to a ‘imperious’ or incidental phenomenon.

## 5. Conclusion

Taking into account chaos and accident as a “need” to stabilize a system can appears a bit hazardous. However, being system-oriented does not mean to be human-centered. Can we accept to loss lives in order to save a system or to save extra lives?

The aim of this article was to emphasize the role of space and time during an extreme event. Decision-makers know that a disaster is a shrinking world and that they evolve within a spatiotemporal system. Space and time are two interdependent variables and this article aims to describe that many phenomena can emerge due to an interactive complexity.

The challenge and recommendation for decision-maker is to analyze a situation and to be able to know if an event, due to its irreversible and unpredictable aspects, can be described as an accident, an incident, an imperious event or a crisis.

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