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Dealing with abnormalities and deviations to enhance resilience in engineering Assets: A critical review from human factors and decision-making perspectives under complex operational contexts

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Abstract. With the growing scale of industrial demands, complexities, and uncertainties around asset engineering and operations due to advanced technology utilization, digitalization, sustainability, new operating models, etc., the sensitive role of abnormalities and deviations towards human safety, systems security, reliability and resilience of engineering assets and industrial systems are becoming even more significant for modern industrial sectors as well as societies in general. In these contexts, the abilities of operators to capture and sense-make early signals that emerge from engineering assets and systems need more attention since it enables them to enhance critical situation awareness (SA) during complex operations. This calls for proactive solutions that can integrate core data with operator knowledge using suitable logical approaches, particularly in a period where there is growing recognition that asset data can provide strong support for engineering and operational decisions in demanding contexts. Based on an ongoing research project, this paper sheds light on abnormalities and deviations; two specific attributes that should be better understood. The purpose is to explore how to capitalize them at very early sense-making stages to enhance situation awareness and thus resilience of dynamic and complex engineering assets and systems. Through a critical review of the current state of knowledge, together with industrial observations, this paper studies these core concepts in detail with due attention to the critical need of so-called priory contextual knowledge and hybrid contextual decision solutions. This R&D work explores proactive possibilities to mitigate inherent potentials for unwanted events and incidents to enhance resilience in the era of digital twins and cyber-physical systems, where complex technologies and operational demands generate new conditions for asset performance.

Keywords: Complex systems, Industrial assets, Digitalization, Abnormalities, Deviations, Contextual knowledge, Advanced situation awareness, Early-sense deviations, Operational risk.

1. Introduction

With increasing reliance on complex dynamic systems, our lives, jobs, properties, and environment are becoming more complex, interconnected, and interdependent [1]. Decades of evidence from a range of industrial sectors have proven that unwanted events and incidents happen continuously in various industrial contexts challenging our conventional comprehension, despite technological and operational advances. Thus, being able to think and act early is arguably a critical attribute to be possessed by

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industrial assets and systems owners, and as Lane [2] emphasizes a small cause in current contexts can make a big difference, for instance in terms of reliability, safety, and security. Throughout the history of industrial evolution, unwanted events have left a range of unresolved questions and issues, which today and tomorrow can become the main concerns due to rapid and fast-tracked growth. With reference to investigation reports about major accidents such as the Fukushima Daiichi Nuclear Power Plant disaster, Deepwater Horizon blowout, Boeing Max-8 crashes, etc. (see for example, [3,4,5], etc.), one can argue that major industrial accidents have indicated the critical role of early warning-signals, pre-accident details, and non-attended data towards the mitigation of exposed risks. For example, detailed analyses of more recent Fukushima Daiichi Nuclear Power Plant [6,7,8], and Deepwater Horizon blowout accidents [9,10], unveil a range of abnormalities and deviations that had given some form of early indications prior to the disaster that had not been duly attended. Arguably, such early indications of abnormalities and potential deviations are vital information of modern complex assets that can be used smartly to inform operators early and promptly about potential conditions that can lead to unwanted events and incidents.

Thus, we argue that the clarity as well as critical roles of systems abnormalities and deviations still largely remain unexplored domains in terms of mitigating systems' inherent risks and major accident potentials. Hence, they are reviewed, and their potential is explored critically in detail in terms of enhancing resilience of modern complex assets and systems.

2. Abnormality and deviation concepts in complex systems: A critical review

Complex systems are formed when relationships between different layers in an industrial ecosystem such as political, organizational, environmental, natural, technical, operational, engineering, etc., are entangled and converged. These layers interact dynamically, and the effects of these numerous interactions propagate throughout the system over time sometimes leading to unfamiliar system behavior [11]. Unique features of complex systems make it difficult to acquire causal explanations of various behavior patterns in a highly dynamic system. Interestingly, Lane [2] asserts that we should change our attitudes about complex systems and that we should learn how to make future states more predictable in specific ways. Complex systems by nature are neither completely predictable nor fully controllable and hence refocus should be made on elements that make the system more fragile and susceptible to perturbations, and at the same time be sensitive to issues that may affect system's well-being [2,11]. However, it can be argued that complex systems naturally possess a wide range of abnormalities despite rules, controls, and standards. We argue that Abnormalities are a natural property of complex industrial assets and systems, they appear explicitly or implicitly as a characteristic of a complex system and can emerge from multiple layers or sources within its context. In addition, changing patterns of behaviors can create a degree of freedom for agents and components to alternate in complicated manners in a dynamic environment [12], resulting in generating various forms of deviations. The inability to understand abnormalities and deviations, lack of awareness of influential sources, lack of knowledge of their consequences, and lack of early preparedness and resolutions to handle them, etc. can expose complex systems to critical conditions. In order to avoid this, boundaries and critical points, so-called tipping points, can be defined according to the features of the system of interest, which can signal if the system behaves in an unexpected manner. According to Burton et al. [1], defining such boundaries and tipping points pre-requires identification of objectives, goals, functions, values, and scope of the system in focus.

From a systems deviation perspective, Kjellén [13] emphasizes on two specific aspects, namely variables and norms. He argues that a deviation occurs when a value of the system falls outside of defined boundaries. Boundaries can be interpreted as planned and intended norms, or constraints and markers, built into the physical system. According to Scheffer et al. [14], in complex dynamic systems, deviations often cover a period when variables start gradually crossing the pre-set boundaries and evolve into a fuzzy manner. Subsequently, the stability of the system can gradually decline, and variables can show unusual fluctuations indicated as early signals [14], yet the recovery chance is relatively high due to slow early transition path. When the system has passed a certain threshold, sudden changes may occur, making the interpretation of the pattern of change, propagation path, and recovery efforts more difficult. Eventually, the system can transit into an uncontrollable mode. Figure 1 illustrates some scenarios related to deviation path profiles in four possible modes.

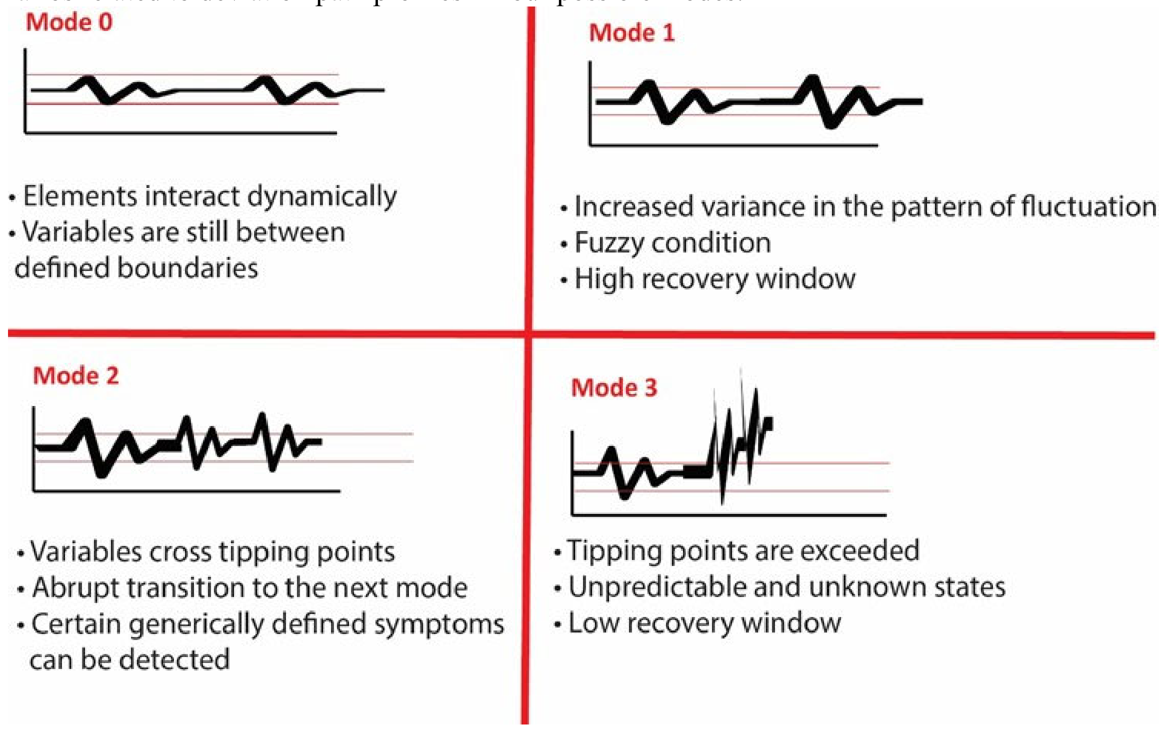

Figure 1. Some scenarios on Deviation path profiles due to inherent abnormalities.

3. Role of knowledge and situation awareness in sensing early- signals

Evidence from serious accidents shows that it is not easy to predict deviation transition paths as the state of the system may show only a few changes before any major deviation occurs [14]. If deviations grow over time to a higher level of severity (for example, Mode-3), activating alarm signals to the operator, then the available capacity to execute counteractions to compensate can become exhausted. If the system is loosely coupled with a higher degree of non-linear interactions, then abnormalities can even propagate through the systems in various paths resulting in complex deviation patterns and unpredictable outcomes. In many industrial contexts, human operators have to monitor the system constantly to locate and define highly likely causes of deviations. They should carry out appropriate remedial actions to mitigate consequences based on prior knowledge, experience, checklist, and pre-defined procedures. Such situations need several sequential search actions through several sources of information which naturally stress operators, especially when alarms are triggered, which may even cause automation bias and lead to erroneous decision-making. When it comes to sensing deviation signals, its potential impact on the level of Situation awareness (SA) of human operators, plays quite a critical role.

Endsley [15] describes SA in terms of three attributes namely: perception of elements, understanding of current situations, and prediction of future states. Bakhshandeh and Liyanage [16] argue however that the current definition of SA cannot address all concerns associated with complexity in a highly dynamic environment, and therefore it is a must to shift the boundaries of knowledge to acquire a higher level of SA, called Advanced situation awareness (Ad-SA).

As Baker [17] emphasizes, linear thinking when dealing with complexity can easily result in blinding humans to a few critical causes and consequences in a dynamic environment. Therefore, any specific knowledge creation process should be able to provide operators with a relatively more comprehensive basis and support, which can cover more engaging layers and even potentially hidden *black swan events*. This creates an increasing focus on the utility of data and data-driven solutions, and particularly automated solutions. However, as Cilliers [11] points out, interpretation of complex systems data to generate relevant deeper knowledge cannot purely be left to an automated system, even though human capabilities in understanding complex behavior in a highly dynamic environment, particularly during early stages are yet far from being perfect. Human operators should still be designed into the decision-making loops in complex industrial processes and operations in a smart manner, since operator experience and tacit knowledge arguably play pivotal roles in terms of safety, security, reliability, and overall systems resilience. This indeed underlines the necessity of a hybrid approach that can capture deeply embedded meanings of abnormalities and deviations in complex industrial contexts to support operational decisions.

From such a perspective, it is argued here (See Figure 2) that a synergy of Human-Machine intelligence is an ideal approach. The underlying need is to generate necessary hybrid intelligence that can in turn enable human operators to make informative decisions by enriching their level of awareness and knowledge of dynamic situations. Such hybrid intelligence is a key factor in creating a specific knowledge type, so-called contextual knowledge. As Brézillon and Pomerol [18] delineate, contextual knowledge is more focused on the relevant knowledge for a given situation, and hence arguably is also quite critical for Advanced SA (Ad-SA). Moreover, contextual knowledge can enhance the human cognitive model for reasoning and decision-making in real-time contexts [19], which will make human operators more focused, ignoring irrelevant data or noise-information, when searching for effective counteraction options. However, as Beyerlein and Lin [20] imply, human knowledge alone is not comprehensive enough to deal with all complex conditions in a dynamic environment.

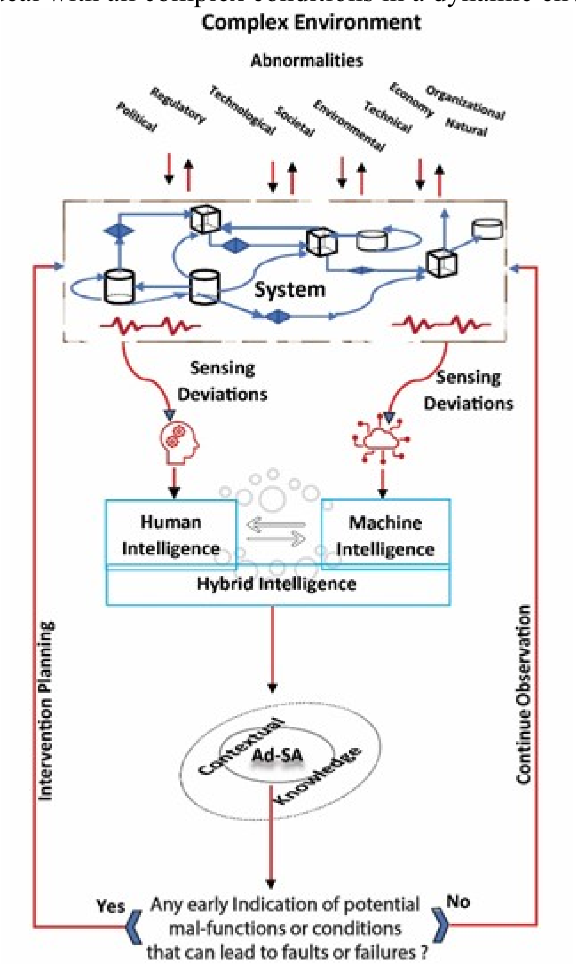

Figure 2. Fusion of Human-Machine Intelligence to generate contextual knowledge and Ad-SA to support early interventions.

From an industrial perspective, there are many efforts underway to develop suitable models to integrate information and interface them with existing knowledge to create better mental pictures for human operators for the purpose of making complex systems more understandable [21]. The central argument here is that as the complexity increases it is essential to explore a new class of models that can capture critical information relatively earlier and connect that with existing knowledge enabling new paths to deal with uncertainties of complex industrial systems proactively enhancing system resilience. This paper sheds more light on this elaborating on a Hybrid contextual decision solution.

4. Towards a Hybrid Contextual Decision Solution

From the point of view of a Human operator who is interacting with a complex and highly dynamic system, it is argued here that a Hybrid contextual decision solution is an increasing necessity in many modern industrial contexts. If adopted smartly, it can help operators deal with deviations, starting from relatively early stages of complex transition processes. The main purpose of such a solution is to provide the basis to enhance the SA (i.e., Ad-SA) of operators through a deeper contextual knowledge with a deeper understanding of ongoing system behaviors, early sense-making of deviations where the potential causes are rooted, and awareness of what their potential propagation paths can be.

However, it is often discussed that the emergent properties of modern complex systems represent a big challenge for predicting future states. But, following Cilliers [11], the presence of these properties does not pose a significant challenge to uncovering the causality. Moreover, the notion of abnormality does not convey the message that a complex system is a chaotic phenomenon, on the contrary, it is acknowledged to have a robust structure. The underpinning central issue is that inherent abnormalities and deviations in a system can be rooted in deep layers and develop into known or unknown paths with potential negative consequences. As Woods [22] points out temporal characteristics of such deviations can provide useful information about the root causes and alternatives for counteraction plans to operators. As a matter of fact, the process should be represented so that operators gain the abilities to track deviations that grow, spread, and subside [22]. Similar views seem to have triggered new efforts in developing semantic modeling of dynamic complex systems to assist humans in making sense of the elements in their interactive systems environment.

Over the years, various mathematical models, qualitative models, and algorithms have been developed based on artificial and computational techniques to create decision support systems (DSS) to assist humans with abductive reasoning, understanding the current situation, and predicting future states based on existing knowledge and experience [23]. However, from a more human operator perspective, Stanton [24] argues that the ways of presenting information based on such new solutions in modern times are heavily affected merely by technological capability rather than human performance or what operators actually need when dealing with perturbations. Therefore, Bordasch and Göhner [23] suggest that additional functionalities need to be added to existing models with specific considerations on human factors in real operational contexts. For instance, recent developments in remote operations in offshore oil and gas sectors have clearly indicated the need to provide operators with not only all real-time data relevant to field operations but also with solutions to create right cognitive maps to enhance SA (Ad-SA) during continuous operations. In such highly interactive and complex contexts, integrating data, utilizing rule-based technologies, using hybrid physics-based and data-driven models in combination with operational experience, modernizing operating procedures, etc. are industrial considerations that can better represent the demanding context and the dynamics of complex systems to help developing right cognitive models and contextual knowledge for advanced SA (Ad-SA). Moreover, ideally, any such contextual decision approach for supporting operators should also take into account human cognitive abilities, capacities, and limitations in dealing with complex data with diverse characteristics. The level of human sensitivity towards different stimuli can vary from person to person. The ability to detect right cues among irrelevant ones, sensitivity to interpret occurring events, and thus to ensure effective perceptual judgment, etc., purely based on cognitive skills and abilities in emerging complex contexts will be quite challenging [16]. Hence, in modern industrial contexts where human operators' work context and task characteristics become relatively more demanding, an ideal solution has to be hybrid in nature where algorithms and applications are integrated with operator experience, based on representative data, logic, and rules, reasoning processes, and interpretation and visualization support to enrich the contextual knowledge and situation awareness.

Based on the aforementioned reflections (and also deviation path profiles in Fig. 1), Figure 3 illustrates two competing scenarios: *alarm-based scenario* and *improved scenario*, for the purpose of sense-making of deviations in complex industrial contexts.

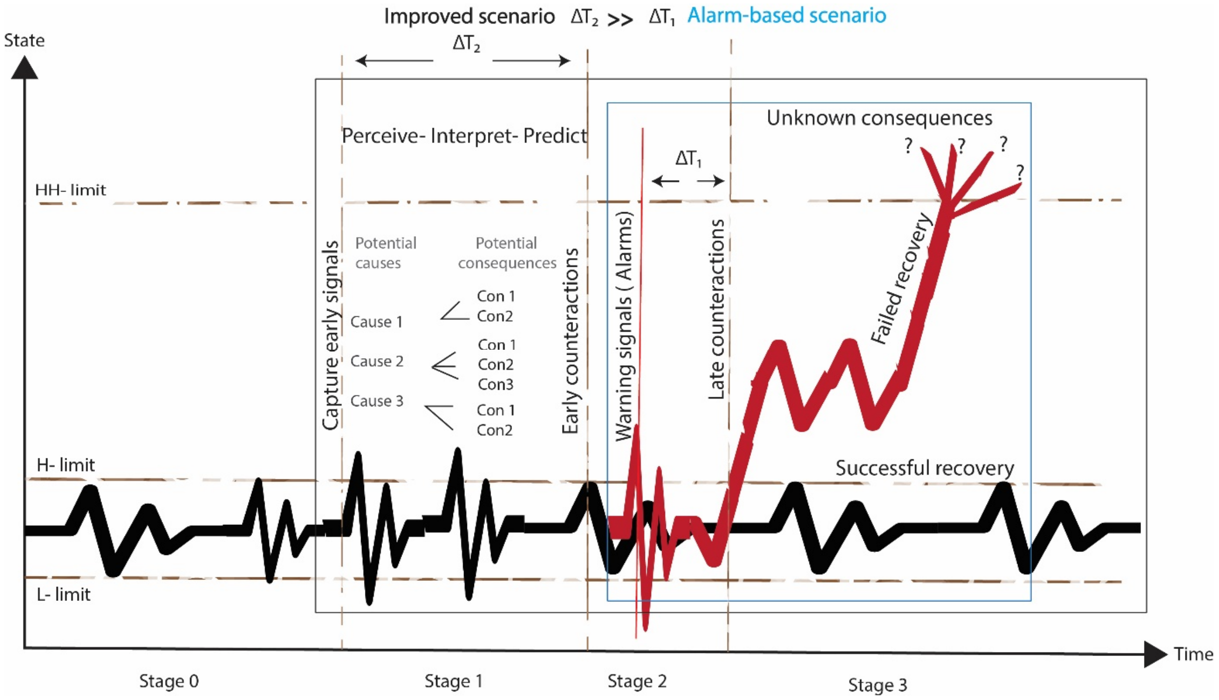

Figure 3. The basis for enabling better system resilience through a hybrid contextual decision solution.

The traditional scenario (ΔT1) is mostly based on an *alarm-based solution* where operators naturally have a limited time window (*Stage-2* + *Stage-3*) to become aware of the situation, detect all root causes, predict possible consequences, and take appropriate counteractions. Many such instances follow pre-defined routines and procedures, with well-known practical limitations and challenges in terms of alarm management as well as operators' cognitive workload [22,32]. Due to a higher degree of interactivity between system elements and the unpredictable behavior patterns of complex systems, considering all possible scenarios under stressful alarm situations is a real challenge both in terms of cognitive demands and execution of right mitigating actions. Thus, in very demanding, highly dynamic, and complex contexts that can be characterized by stress-inducing alarm patterns and late counteractions, a failed recovery tends to be the highly probable outcome as many major industrial accidents (e.g., Chernobyl disaster, Fukushima Daiichi Nuclear Power Plant disaster, Deepwater Horizon blowout, Boeing Max-8 crashes, etc.) have underlined. Therefore, to tackle these problems, human operators need to be attentive and resourceful to be able to maintain a proper level of awareness of what is changing in a given context in modern industrial systems. Any approach to capture the most likely scenarios in advance allowing operators to prioritize them according to an acceptance criterion, is of immense benefit, particularly in emerging contexts. This is the basis for the *improved scenario* (ΔT2) where operators are given the ability to work within an extended intervention window *(Stage-1* + *Stage-2* + *Stage-3*) so that they acquire possibilities to perceive relevant information early, interpret potential causes, predict potential consequences in real-time, and prioritize their interventions appropriately. As Figure 3 illustrates, there is a relatively larger window of time (ΔT2 >> ΔT1) for operators to sense deviations and take proactive measures. Once an early deviation signal has been captured and communicated by a technical solution,

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human operators can trace the potential causes of the early signal and take necessary actions, for instance, to prevent the system from reaching a more critical state where an alarm system would naturally be triggered. Such an early sense-making approach, characterized by capturing of early signals, more time to perceive-interpret-predict, and implementation of early counter actions, can naturally enable effective use of knowledge, time, and capacity, leading to successful recoveries, thus preventing costly downtime, damage to equipment, and potential safety hazards. As aforementioned, a whole range of major accidents inclusive of the Fukushima Daiichi Nuclear Power Plant disaster, Deepwater Horizon blowout, Boeing Max-8 crashes, etc., as well as many other unwanted events and incidents that occurred in recent years, have already indicated the practical utility of such early sense-making efforts towards critical operational decisions.

5. Conclusion

The paper emphasized that abnormalities and deviations are inherent characteristics of complex industrial systems, and deviations occur during interactions across pre-defined boundaries. Abnormalities may not be desirable, but they do not necessarily indicate failures or malfunctions until some form of deviation begins to occur. At best, tipping points can be pre-defined, according to matching criteria and expected values, to detect such deviations much early and subsequently to track the potential propagation paths ahead of time. Abilities for sense-making of an industrial system's early signals play an increasingly pivotal role by enabling operators to plan intervention measures and to deal with unwanted conditions effectively ensuring resilience. Through a critical review of these core concepts with respect to modern industrial contexts, this paper underlined the necessity for priory contextual knowledge and hybrid contextual decision solutions to mitigate inherent potentials for unwanted events and incidents. Reflections here are based on a critical review of the current state of knowledge and various industrial observations. The real practical utility of such solutions is clearly evident with respect to recent cases of unwanted events and incidents, and importantly more so for emerging complex industrial systems in the era of digital twins and cyber-physical systems.

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