A Resilience Markers Framework for Small Teams

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Abstract. Processes that enable an effective response to unexpected events and vulnerabilities that lie outside the scope of formal procedures can be described as being resilient. There are many such descriptions of resilience within and across different domains. Comparison and generalisation is difficult because resilience is not a component of a system and should be understood as an emergent property. Here we provide a framework for reasoning about resilience that requires representation of the level of analysis (from the individual to operational), a traceable link from abstract theory to specific observations, resilience mechanisms, and contextual factors. This moves forward an agenda to systematically observe concrete manifestations of resilience within and across domains. We illustrate the application of the framework by considering a case study of the performance of Nuclear Power Plant (NPP) operators in an experimental scenario. This paper focuses on the small team level of analysis. The framework presented here provides the basis for developing concrete measures for improving the resilience of organizations through training, system design, and organizational learning.

1. Introduction

Resilience generally means the ability to recover from some unexpected event, or to avoid accidents happening despite the persistence of poor circumstances. During everyday routine, a system has the potential for resilient performance. The aim of the framework presented in this paper is to provide a means of identifying this potential. This notion of identifying potential is less about minimising risks associated with unexpected events and more about promoting things that the system does well so that it is better able to cope. For example, if people are experienced and well-trained, this is known to help coping with the unexpected. The ability to deal successfully with unexpected events (i.e. resilience) is, to a large extent, dependent on a specific set of skills, practices and attitudes, which we call the resilience repertoire. For this potential to translate into resilient performance, it needs to be supported by appropriate

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resources, system characteristics, and organizational structures. However, the underlying repertoire of activities that allow for resilience is poorly understood. The resilience markers framework presented in this paper aims to provide staff, trainers, and management with a way of identifying things that they do well, so that they can be enhanced and protected in future programmes and designs. This is particularly pertinent where resilience mechanisms are implicit or invisible and would otherwise face the prospect of being 'designed away' [1, 2].

This paper is divided into five main parts. Section 2 provides a background to our resilience perspective. Section 3 reviews resilience studies, which provides motivation for the proposed framework. Section 4 introduces notions related to the Resilience Markers Framework. Section 5 relates empirical data from the Nuclear Power Plant (NPP) domain to the framework. The paper finishes by reflecting on how the framework encourages a grounded resilience analysis that links abstract theory to concrete observations that can provide the foundation for within and cross study comparisons.

2. Background

The Resilience Markers Framework proposed in this paper builds on work in Resilience Engineering. Along with others, this field has questioned traditional approaches to safety, especially when trying to account for responses to unexpected events and vulnerabilities that fall outside the scope of formal procedure and design. This has consequences for the underlying model of safety, i.e. the elements and interactions a model emphasises. This also has implications for perspectives on training, and interaction analysis and design.

Historically, there has been much more focus on why things go wrong than on why they work well. Conventional engineering approaches to ensuring safety attribute failure to a system component (human or technological) rather than the system as a whole [3]. When systems fail, the cause is often classified as *human error* or a *technical problem* associated with a process. Attributing blame to a faulty component offers a discrete solution for management: the component can simply be replaced, fixed, or retrained. In reality, however, the ability of a socio-technical system to avoid, detect, and recover from failure requires a deeper understanding. This could involve a researcher understanding the system and advising on change, or the system understanding itself so it is in a better position to prepare for and respond to disturbances. Avoiding, detecting and recovering from failure is different from traditional approaches to safety which look at risk analysis and prevention, and traditional approaches to human factors that largely focus on improving task and system design. Instead, resilience focuses on action to compensate for poor behaviour, poor design, poor systems and poor circumstances. This is especially pertinent outside design-basis, where a surprise has occurred and defence-in-depth is challenged (i.e.

where several technical, social, procedural and behavioural layers jointly protect the system).

A systematic evaluation of risk reveals that a safety-critical system must have the capacity to perform resiliently 'outside design-basis'. We use the phrase 'outside design-basis' to denote instances where the system must cope outside its formal design parameters. We reject the popular notion of 'beyond design-basis' for two reasons: the first is that it has an unfortunate nuance of being 'beyond' normal notions of safety and design, whereas we see the relationship between resilience, safety and design as being much more equal and complementary; the second is that 'beyond design-basis' suggests accidents that were not fully considered in the design process because they were judged to be too unlikely. This second point implicitly emphasises extreme and rare events to the detriment of everyday disturbances and the slow erosion of resilience. We still believe these extreme events, described by Westrum [4] as irregular and unexampled, are of key interest to resilience, but not to the exclusion of mundane disturbances.

Underlying models of safety have received a lot of attention and development in recent years. Here practitioners and researchers have found limitations in traditional approaches, e.g. that they are based on a component (hardware) reliability model [5], that they are too linear and sequential [6], and that they do not adequately take a systemic view into account [3]. Lundberg et al. [7] highlight the importance of underlying safety models with their reference to the 'What-You-Look-For-Is-What-You-Find' or WYLFIWYF principle; as these models will shape what elements and interactions are investigated in context and what remedial actions are taken. For example, traditional models have been criticised for a 'blame-and-train' approach in the wake of incidents. Here the designed system is presumed to be faultless and the humans are blamed and trained to better fit the designed system (see parable of the suit fitting in [8]). In contrast, the discipline of HCI (Human-Computer Interaction) will often defend the human contribution to incidents, as it is assumed that good design can prevent error and so discount the need for training. Acknowledging the now prevailing view that errors cannot all be designed out of the system Kontogiannis and Malakis [9] provide a framework which looks to proactively detect human error so it can be better managed in context.

Many case studies [e.g. 10] have identified potentially high risk situations where the formal procedures were inappropriate, not correctly executed, or embellished to keep things working. People will appropriate technology in unanticipated ways to improve their effectiveness, efficiency and safety in everyday work [2; 11]. However, designers rarely pick up on these behaviours or accommodate appropriation in systems, as they see it as being outside their scope or the information does not get fed back to them in the right way [5]. Exacerbating the issue, adaptations to local circumstances and compensation mechanisms for deficiencies and disturbances can remain *invisible* or *implicit* to the people in the situation [1, 2]. Here, it is especially important to try to 'see' implicit behaviours and understand interactions so that systems can be designed to explicitly support them.

Dealing with high risk situations is facilitated by designs that provide operators with an opportunity to adapt performance [12]. This can enable the generation of new artefacts (that facilitate communication between operators) or new procedures that increase the overall safety of the socio-technical system. A safe interaction can be described with reference to markers that indicate strategies that make an interaction safe. By improving our understanding of interaction, it may be possible to discover enabling conditions for the generation of new resilient strategies that are both able to spontaneously emerge and persist over a long period of time. Importantly, this is not a list of static behaviours that ensure resilience; instead, markers identify potential strategies that may be created and invoked in response to the specifics of the situation at a particular point in time.

Traditional safety and human-centred perspectives are not orthogonal to resilience. None are sufficient for safety alone and their differences and contributions should be recognised. We focus on aspects of resilience which emphasise the propagation and transformation of information in a system [e.g. 13]. Resilience involves interactions that happen inside and outside the head, and so we observe interactions across tools, artefacts, people and representations [e.g. 14]. By looking at these interactions, we focus on strategies that compensate for poor behaviour, poor design, poor systems and poor circumstances. These concerns are critical when the system has to operate outside design-basis. To help maintain, develop and apply these strategies we offer a framework which moves forward an agenda to systematically observe concrete manifestations of resilience within and across domains.

3. Review of Resilience Studies

Resilience Engineering is an emerging discipline, which continues to develop research methods and perspectives. In this section we review a selection of resilience case studies and analyses to provide a motivation and foundation for the proposed framework. Four papers are taken from the latest Resilience Engineering symposium in 2008; one study is from a Resilience Engineering book; one study is from a Resilience Engineering workshop; one study is from a safety related conference; and the remaining seven references are from safety orientated journals and a book. This is not a comprehensive literature review, but is illustrative of the work and issues in the area. These case studies involve different domains and different units of analysis, but share a resilience theme in common. The studies exemplify behaviours which can be considered resilient. However, they do so in different ways. Two main issues emerge from this review which provides the motivation behind our proposed framework: 1) the papers fail to build on each others' work and there is no shared analytic framework; and 2) it is not common for papers to have a traceable line from concrete observations to high-level resilient principles.

Mumaw et al. [11] take a cognitive field study approach to investigate the task of monitoring in the nuclear power plant control room environment. This approach emphasises cognitive and collaborative processes, and ultimately the way information is processed in the environment. They observed operators using adaptive strategies to reduce cognitive noise and improve the salience of important information in the environment, create new relevant information, and offload cognitive demand. The operators do this by using their environment intelligently and compensating for poor design. Rasmussen [15] called this intelligent adaptation of design “finishing the design”. Examples include leaving doors of important instruments and displays open to increase their salience, putting Post It notes on alarms that have extra information associated with them, and resetting alarm parameters so that operators are alerted to rising levels associated with that instrument automatically. These examples are all beyond the intention of the designers of these systems. Design implications include allowing operators to carry out this behaviour more formally, and designing systems to facilitate this.

As shown in Table 2, Mumaw et al. [11] present their observations in a hierarchical framework including a main category of strategy (e.g. strategies to maximise information extraction from available data), the actual strategies (e.g. reduce noise and enhance signal), and then concrete examples that ground the strategies in context. This is a similar format to Kontogiannis and Malakis [9] who present human error detection and identification strategies, such as a main category of strategy (e.g. strategies in outcome-based detection), the actual strategy (e.g. verifies the accuracy and reliability of information), and concrete examples (e.g. a trainee pilot did not cross-check an oil pressure gauge by reading other instruments and drew the wrong inference from this faulty indicator). There can, of course, be multiple layers from the abstract to the specific, but three seems an adequate number to allow for the very general, details of the general, and specific examples.

Studies often present their data using different levels of abstraction, but do so in different ways, using different categorisation schemes. For example, Costa et al. [16] apply several Cognitive Task Analysis techniques to understand a nuclear emergency response situation, and recognise sources of resilience and brittleness from their analyses. Also, Hale and Heijer [17] do a general analysis of the Dutch railway system and then reflect on its resilient attributes. Their analysis uses a finer grained categorisation with eight different criteria, rather than a resilience versus brittleness distinction. For example, the first criterion is: 'defences erode with production pressure' (Section 4.2.iv lists all eight criteria). More detailed criteria provides more guidance to the analysts, but this in turn could be considered constraining compared to a looser categorisation.

A different categorisation is offered by Malakis and Kontogiannis [18] who identify failure-sensitive strategies of Air Traffic Control (ATC) operators in the training simulator. Five of these are individual cognitive strategies: recognition, managing uncertainty, planning, anticipation, and managing workload; and four are joint cognitive strategies: coordination, information exchange, error management and workload distribution management. These can provide insight into the local adaptations of actors in the form of cognitive strategies to support resilience. From a higher and more organisational perspective Johansson and Lindgren [19] offer a set of resilient dimensions to assess a system. Four of these dimensions focus on detection properties (e.g. capacity to predict changes in the process/environment), and nine focus on adaptation properties (e.g. potential for learning from past experience). As shown in Table 2, the reporting of these categorisation schemes are more removed from concrete observations when compared to Mumaw et al. [11].

Looking more closely at individual cognition, Back et al. [20] use reflection as a mechanism for explaining how people distinguish between routine performance and adaptation to novel contexts. Looking at the same level, Bracco et al. [21] propose the SRK (Skills-Rules-Knowledge) ladder [22] as a mechanism for distinguishing whether a response to the context is at the appropriate level of cognitive activity. This again links to a distinction between routine and novel responses. These approaches focus largely at the individual level of resilience interaction but framed under different mechanisms.

Resilience at the small team level focuses particularly on how people manage different workloads, develop individual and collaborative strategies, compensate for deficiencies in their environment, and avoid and recover from collective errors [e.g. 1, 2]. Our previous work conducted within London Underground control rooms identified factors that contributed directly to overall system safety, which fall outside formal design-basis [23]. Factors included the ability of staff to manage uncertainty, to learn in an exploratory way, to reflect on their actions, and to engage in problem-solving that has many of the hallmarks of playing puzzles which, in turn, supports exploratory learning. This work provided support for Rochlin's [12] suggestion that system features need to promote resilient performance by accepting mistakes and supporting the duality of system views; i.e., there is tolerance for perceiving the same system in different ways.

The original conception of the "markers" approach, on which this paper builds, enabled one to specify different levels of granularity [24], as shown in Table 1. Here, the different levels are individual, small team, operational, plant and industry. Limitations of this included an underdeveloped conception of the mechanisms behind the resilience and guidance on how one would observe these in practice. Indeed, no specific resilient observations are presented in the table.

Table 1: The original conception of the markers approach [24]

Granularity	Examples of Vulnerabilities	Resilient Manifestations	Resilient Markers
Individual Level	Errors in procedural routine	1. Reflection 2. Cue creation	Providing an opportunity for meta-cognitive activities.
Small Team Level	Coping with increased demand	1. Buffering 2. Work shadowing 3. Artefact use	Optimised flow of information and physical layout. An understanding of artefact use, social and evolutionary conditions.
Operational Level	High complexity	Error recovery	Symptom-based emergency procedures, automatic safety systems, strategic crew leadership.
Plant Level	Plant shut downs or failures to start up, major accidents	1. Plant safety record 2. Response to major disturbances	Maintenance regime, plant upgrades, risk analysis, training programs.
Industry Level	Political and regulatory intervention	Performance necessity and availability of alternatives	Regulatory compliance, public/political perception, cost-benefit ratio, competitiveness.

Exploring how traceable studies are from the abstract to the concrete, Table 2 shows five studies that operate at different levels of abstraction. There are three different levels of abstraction presented here: high-level abstract principles, mid-level abstract strategies, and low-level examples. This table shows that resilience studies. Work by Mumaw et al. [11] and Kontogiannis and Malakis [9] seem most comprehensive for this type of analysis as they give details and examples at each level of the hierarchy. The fact that clear examples are included in this work makes it much more concrete and accessible.

Table 2 makes it more apparent that there are gaps in the studies and frameworks that some propose. In general, papers that remain solely at the higher markers level risk being too abstract and hard to associate with the specifics of practice. In contrast, papers that remain solely at the lower concrete observation level risk being too descriptive and specific to a particular context, making it hard to generalise. A traceable framework will better link theory to evidence, and better facilitate the potential for studies to start to build on each other’s work.

Taken together, this literature shows exploratory attempts to get to grips with resilience analysis in research and practice. Points to note are that not all studies have a clear link between higher level resilience theory and concrete observable data; studies can be focused on different levels of granularity (e.g. from the individual to the organisational); there is no agreed criterion or approach for such analyses; and the analyses fail to build on each others' work. In the following section we propose a framework which captures some of the important mechanisms behind resilience, with a traceable hierarchy at its core.

Table 2: How observations in the literature relate from high-level principles, to mid-level abstractions, to examples and observations.

High-level abstractions	Mid-level abstractions	Examples
A. Relaxing efficiency goals. Johannson and Lindgren [19]	A1. Not identified in paper.	Not identified in paper.
B. Coordination. Malakis and Kontogiannis [18, p. 198]	B1. Team coordination [18, p. 198]	Not identified in paper.
	B2. Shared situation understanding [18, p. 198]	Not identified in paper.
	B3. Intent Communication [18, p. 198]	Not identified in paper.
C. Strategies to offload cognitive demand. Mumaw et al. [11, p. 50]	C1. Create an external reminder for monitoring [11, p. 50]	"Operators may leave the door open on a particular strip-chart recorder to make it stand out from others when it is important to monitor that parameter more closely than normal." [11, p. 50]
	C2. Create external cues for action or inaction [11, p. 50]	"... operators may put paper sticky notes on the control room panel to flag unusual indicators." [11, p. 50]
	C3. Employ additional operators [11, p. 50]	"Several operators mentioned that when workload gets high and there are too many monitoring demands, another operator can be dedicated to a small set of indicators or to the alarm screen." [11, p. 50]
D. Strategies in outcome-based detection. Kontogiannis and Malakis [9, p. 701]	D1. Examines relational and temporal patterns of change [9, p. 701]	Monitoring trend information [9, p. 701]
	D2. Considers a model of influences and interventions [9, p. 701]	The accident of British Midlands 092 in Kegworth (1989): a (healthy) engine was shutdown unwittingly which also appeared to cure the symptoms, but the real problem was masked. [9, p. 701]
	D3. Verifies the accuracy and reliability of information [9, p. 701]	Trainee pilot did not cross-check an oil pressure gauge reading by reading other instruments. [9, p. 701]
E. Not identified in paper. Wears et al. [2]	E1. Not identified in paper.	Status boards "have developed complex, informal and unofficial functions that are arguably more important to the smooth functioning of their units than just tracking". [2]
		Informal networks of workers "serve to 'test' and 'approve' changes and additions to the board's language and symbols". [2]

4. Resilience Markers Framework Description

We introduce the Resilience Markers Framework in two parts. The first elaborates on the traceable hierarchy at the core of the framework, composed of a markers level, a strategies level, and an observational level. The second expands the strategy level to reveal mechanisms that come into play in episodes of resilience. These mechanisms play out and influence what is actually observed in practice.

4.1. Hierarchical Core: Markers, Strategies, and Observations

Reviewing previous literature (see Section 3), many of the studies observe resilience behaviours or events at different levels of abstraction, but they do not have a common vocabulary or structure to build on each other. We develop the markers approach described by Back et al. [24] into a traceable hierarchy at three different levels of abstraction. The top level is the resilient markers: there will not be many of these and they will generalise across domains. The middle tier is the strategy level; these expand on the detail of the markers but are still not grounded in the specifics of a particular context. The mechanisms behind the strategy level are expanded upon in Section 4.2. The lower tier accounts for the observations of resilience, which is the output behaviour and what actually happens in practice. Attributes and an example of the different levels are captured in Table 3.

Table 3: Table to show levels, attributes and an example of the hierarchy

Level	Generalisability	Quantity	Example
Markers	High	Low	Maximising information extraction
Strategy	Moderate	Moderate	Creating an external cue
Observation	Low	High	A paper clip to bookmark a page in the procedure someone is following

4.2. Expanding on the Mechanisms Behind the Strategy Level

The framework that we describe here captures a relevant ontology to assess resilient interaction. The framework reflects the markers, strategy and observation hierarchy, but expands the factors that are involved at the strategy level. The strategy level contains four elements that are important in shaping the manifestations of resilience (see Figure 1). The elements were generated by reflecting on previous research, on our own studies, and on discussions at the Resilience Engineering Workshop in

Pukeberg, Sweden, 2009. They were found to provide leverage for sense-making when looking at resilient scenarios. To test and consolidate this approach we validate it using a case study involving nuclear operator crews (Section 5).

We expand on the four elements in the middle of Figure 1 here:

i) Resilient Repertoire: A resilience repertoire encompasses those skills, strategies, and competencies that comprise a system's responses to threats and vulnerabilities which are outside design-basis. If the threat is too much for the system to handle, and its resilience repertoire insufficient or misapplied, then system performance will degrade or fail.

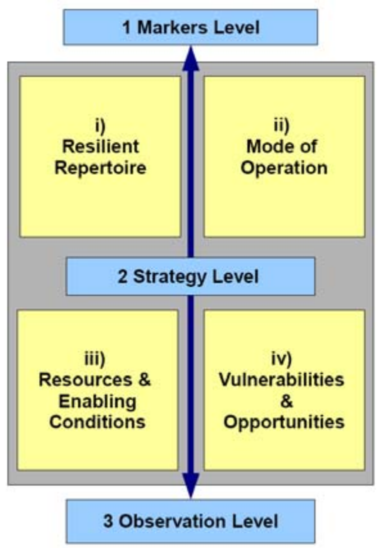

Figure 1: Resilience Markers Framework. This framework has the (1) markers, (2) strategy and (3) observation levels hierarchy running through its core. The strategies part is expanded into four interacting elements: (i) a resilient repertoire; (ii) mode of operation; (iii) resources and enabling conditions; and (iv) vulnerabilities and opportunities. These elements are described in the body of the text.

Furniss et al. [25] suggest that resilience responses can be of two kinds: they can be created, in which case a high degree of innovation is used, or established resilience responses can be reapplied, adapted, and shared within a system. These two kinds of activity suggest how the resilience repertoire can be managed and developed. For example, a recent case was reported of someone using their iPhone to aid their mountain rescue using the GPS and map software on their phone [26]. This novel use of the phone's functions suggests a development of this person's resilience repertoire and something they could reuse and adapt in other situations. This resilience strategy could also spread to other people, maybe by the reporting of the story in [26] or even by reading this paper. Similarly, best practices that lie outside design-basis may be created through inspiration or perspiration in organisations, and once created these may be propagated within and between groups formally or informally. These mechanisms suggest a functional role for management, training, assessment and organisational learning to enhance resilience.

ii) Mode of operation: This refers to the way that the system has organised itself. Different modes may be apparent in some contexts, e.g. Blandford and Wong [27] observe 3 distinct phases in emergency medical dispatch (EMD) work: (a) routine operation, (b) transition to a major incident, and (c) major incident declared. The mode of operation will impact on the resources and enabling conditions available for the resilience strategies; e.g. when a major incident is declared in phase (c) of EMD work, a separate team is moved to a dedicated control room to manage the incident.

The mode of operation can refer to the style or structure that a system implicitly or explicitly adheres to. Where this works well, it can be useful for making available suitable resources for dealing with the problem. Where it works badly, it can confine and restrict the potential for a suitable response, leading to performance degradation and failure. For example, Weick and Sutcliffe [28, p. 4-18] describe an incident at the Cerro Grande where a planned burn of wildland got out of control and caused $1 billion in damage, destroying 235 homes and 39 laboratories. The fire was fought by 1000 firefighters over a 15 day period. A factor which contributed to the disaster was confusion about a policy (the mode of operation) which directly affected the availability of resources to fight the fire (resources).

> The person in charge of the wildland fire needed more resource to contain it, but the dispatchers would not grant this extra resource unless the 'prescribed fire escaped and was declared a wildfire'. The mode of operation was dependent on the perceived threat, and the person in charge of the planned burn did not want to admit to a larger threat but wanted the increased resource. However, the dispatchers would not release the resource until the threat was officially declared 'a wildfire'. Under those circumstances they could act according to their interpretation of the policy. Of course, whilst this haggling about policy continued the fire grew (adapted from [28, p. 4-18]).

In the terms of our framework, this example provides a link between a perceived vulnerability, a change in the mode of operation, and the subsequent resources available to deal with the threat.

iii) Resources and enabling conditions: These are the hard and soft constraints that influence whether a strategy can be enacted. For example, the personnel and resources to fight the fire referred to in the Cerro Grande example above limited their response to the threat. Also, Blandford and Wong's [27] observation of changing to phase (c) in their EMD context might be constrained by the availability of staff to form a separate team and whether there is the room and other necessary resources for them to have a dedicated control room to manage the incident.

iv) Vulnerabilities and opportunities: Responding to vulnerabilities and opportunities is a central part of resilience when these reactions are outside design-basis. There is much evidence for vulnerabilities in the literature. For example, vulnerabilities are captured in the threats detailed in case studies like the terrorist attack on 9/11 [29], the natural disaster of Hurricane Katrina [30], and the eroding resilience and fluctuating demands of an emergency medical department [31]. All of these case studies describe situations where the system needs to respond to some acute or ongoing stress for the sake of resilience.

Unlike the studies above, which use a more exploratory approach to vulnerabilities and resilience, Hale and Heijer [17] use a structured approach to their analysis. They assess the resilience of railways across the eight criteria (listed below) that indicate different types of vulnerabilities. For example, with reference to the seventh criterion, they observe that the railway system scores low on resilience; i.e. it does not respond flexibly to change but instead stops and restarts when the system's parameters return to an acceptable state again (what they call a 'stop-restart philosophy').

1. Defences erode with production pressure
2. Past performance leads to complacency
3. No shared risk picture
4. Risk assessment not revised with new evidence
5. Boundary breakdown impedes communication
6. Not high enough devotion to safety
7. No flexible response to change
8. Safety not inherent enough in design of system

Vulnerabilities are commonly referred to in the resilience literature because of their intrinsic orientation around safety. In terms of ambulance dispatch, a vulnerability could be a train crash which would be a major incident needing a coordinated EMD response across different sectors; it could be the computer systems failing, needing a return to the manual paper system; or could involve an ambulance breaking down, needing another vehicle to be assigned to the incident.

Opportunities are referred to less because they engage with performance enhancement, which is not inherently linked to safety. For example, Furniss et al. [32] discuss how resilience is pertinent to usability practitioners. They suggest that positive interactions can become the focus of the study; this contrasts with the focus on negative interactions associated with accident prevention. Here, practitioners use resources (e.g. people, methods, and strategies) to their advantage so that projects run as effectively and efficiently as possible within pragmatic constraints (e.g. time, money, expertise). These practitioners work in a competitive environment and so must minimise effort and maximise gain from their work. This is for the sake of their clients and their viability as a business. In terms of ambulance dispatch, opportunities may present themselves for performance improvement, e.g. observing better strategies for managing dispatch in others might lead to the adoption of those strategies in oneself. Also, new technological advances may provide an opportunity for current EMD systems to be improved and upgraded; e.g., GPS systems were installed when they became available, which allowed dispatchers to see where emergency vehicles were located in relation to incidents on an electronic map.

5. Case Study: Nuclear Power Plant (NPP) control room crews analysis

We have used the Resilience Markers Framework to re-analyse data from 14 nuclear operator crews that took part in an experiment at the Halden Man-Machine Laboratory, a full-scale nuclear control room simulator. The crews had to deal with very challenging emergency scenarios in a Pressurized Water Reactor (including a complex loss of feedwater scenario and a complex steam generator tube rupture scenario) [33]. Emergency operation in nuclear control rooms is highly procedure-driven. The scenarios in this experiment were designed to challenge the procedures, for instance by creating conditions where indicators that usually provide diagnostic information for the procedure work are missing or provide incorrect information (e.g. missing radiation alarms). In this situation, the operator crews must rely on their plant knowledge, situational awareness, and problem-solving skills to diagnose the problem by other indicators (e.g. steam generator level). Such situations are characterised by high cognitive complexity and information load, moderate to high execution complexity, and moderate time pressure. They place high demands on crew communication, require a teamwork approach to problem solving, and rely on operators' expertise.

The data from the original study was collected and analysed for the purpose of testing different Human Reliability Assessment (HRA) methods. Resilience Engineering and HRA are considered by some researchers as opposing or incompatible approaches [34], while others consider them complementary [35]. What is of particular interest here is we can look at the same data source from two different angles.

The data consisted of: full video recordings of each crew in each condition from four different camera angles; descriptions of the scenarios that formed the simulations; and crew performance summaries written by process experts who observed the crews, which included their comments on crew performance. We also had discussions with a process expert who helped collect and review the data for the original study.

We focus here on providing a proof of concept rather than a comprehensive analysis. We describe populating the framework in the next two sections.

5.1. Method

This method section describes the first three stages of analysis: familiarising ourselves to the context and the available data; identifying evidence of resilient episodes in the data; and categorising the evidence in terms of the analytic structure of the framework (i.e. markers, strategies, observations, vulnerabilities, resources, and the mode of operation). The results section (Section 5.2) presents five resilient episodes that link together parts of the data using the framework. In practice, there may be iteration between these stages. We describe our experience of using the framework in the discussion section.

Familiarisation

To populate the framework we first familiarised ourselves with the context by studying the video recordings. The initial aim here was to observe concrete manifestations of resilience in crew performance. However, insights from these recordings were limited beyond getting an idea of the pacing and context because the crews spoke in a foreign language, which was unfamiliar to the two analysts. After this, the analysts (the first two authors) divided the crew performance summaries between themselves so that evidence of resilience episodes could be identified.

Identification

The crew performance summaries consisted of the crews' main actions with written process expert commentary organised chronologically as the crews' activities unfolded. The two analysts read through the summaries and noted evidence of resilient observations and vulnerabilities that presented themselves; e.g. this excerpt was noted as a positive resilient strategy as work was shared when the system became stressed: "Good division of work, SS takes some of the load from the RO." Here, the Shift Supervisor (SS) is the senior person in charge who oversees the work of the Reactor Operator (RO) and the Assistant Reactor Operator (ARO) who monitor and control the plant. To facilitate collaboration, the analysts recorded the elements of resilience they identified on Post It notes so that they could be discussed and categorised on a whiteboard. This identification stage also included identifying markers and strategies that were already in the literature that would populate the framework at its higher levels (e.g. see Table 2).

Categorisation

The main elements of the framework were written on the whiteboard (i.e., markers, strategies, observations, vulnerabilities and opportunities, and resources and enabling conditions), and Post It notes representing empirical events and commentary recorded in the crew performance summaries were grouped under the relevant headings. In the analysis many of the markers and strategies were taken from the existing literature, but the observations, vulnerabilities and resources and enabling conditions were specific to the data. We coded the Post It notes so they could be linked back to their place in the literature and the crew performance summaries. This was important because the Post It notes lost their context when divided between all the headings. Coding allowed the individual elements in the framework to be traced back and linked together, so they could be considered in ‘resilient episodes’.

5.2. Results

To make the analysis more accessible to the reader we extract and describe five resilient episodes which show how our framework fits the data. This gives a better narrative behind the resilience mechanisms within each episode. The elements of the framework are in **bold** type.

<u>Episode 1: Wrong procedure</u>

While in the steam generator tube rupture scenario the RO said, “We are actually in the wrong procedure,” to the rest of the crew. This is an **observation** of resilience which we labelled: 'admitting to following the wrong procedure'. We related this to the **strategy** 'provision of feedback to enable error correction' [18] and the broader **marker** of ‘recognising and responding to failure’. The threat was that an incorrect procedure was selected. **Vulnerabilities** included that the RO did not ask for help from the SS when he could have done, the ARO did not answer with trend information which he should have done, and the team did not appear to have a working hypothesis of what was happening. The **enabling conditions** which allowed the resilient strategy to be enacted included the detection of the mistake by the RO, and that the team had a culture where this mistake was shared rather than hidden.

We judged this episode of resilience as significant because actions by one member of the crew increased the likelihood that the crew remained in control. The crew member became aware of a threat, raised it with their colleagues for consideration, and without this acknowledgement the team would not have had the opportunity for corrective action. The situation would have developed and could have gone beyond their control. This is an example of taking steps to proactively manage performance variability as events unfold.

<u>Episode 2: Preparing for work</u>

As the steam generator tube rupture scenario developed, the RO asked the SS for advice on what to do. The SS reasoned that they had done what they could do for the time being and continued to gather information and try to work out what was happening. Rather than have the RO do nothing, the SS told him to wait and look ahead in the procedures. We recognised this as a resilient **observation**. We related this to the **strategy** 'exploiting less busy periods to prepare for future work' [18]; and the broader **marker** of 'preparation'. The break in work allowed the **opportunity** for the crew to prepare for future work. There was added time, which was a **resource** for this strategy, and the SS's leadership of the situation was another **enabling condition**.

We judged this episode of resilience as significant because the crew is anticipating demand in the future and take steps to increase their potential to respond adequately. They exploit the opportunity of having extra time to invest in preparation, which could pay dividends if and when the scenario develops further. This is an example of proactively investing ‘now’ so performance variability can be better managed later.

Episode 3: A paper clip as a bookmark

The SS instructed the RO to put a paper clip in the procedures so that they could find where it referred to the reactor coolant pressure in the future. We recognised this as an **observation** of resilience. We related this to two similar **strategies** in the current literature: 'create a new indicator' [11] and 'cue creation in action' [20]. We then went up a level to the **marker:** 'strategies that maximise information extraction' [11]. The **vulnerability** was knowing that the information may be hard to find in the future. The **resource** was the availability of a paper clip in this situation.

We judged this episode of resilience as significant because the operators seem to be aware of their cognitive limitations and take positive steps to mitigate errors and delays in relation to these. By using something as simple as a paper clip to augment their cognitive environment, they positively skew performance variability in their favour. This strategy enhances performance and is outside design-basis. By itself, using a paper clip as a bookmark may seem trivial, but coupled with a complex scenario and time pressure for finding a specific place in the procedures this could prove distracting and detrimental to performance.

Episode 4: Sharing workload

Under a high workload, the RO asked the SS to take care of the alarms which we recognised as a resilient **observation**. We related this to two similar **strategies** in the current literature: 'employing additional operators' [11] and 'team coordination' [18]. We then went up a level to the **marker:** 'Managing workload' [18]. The **vulnerability** was that mistakes are more likely under a high workload. The **resource** was the spare capacity of the SS to support the work, and their team working ethic contributed to the **enabling conditions**.

We judged this episode of resilience as significant because the team recognises the vulnerability of what a high workload can bring and self organises to better manage this performance variability. It seemed significant to the two analysts that the RO asked their SS for help rather than coping as best they could and taking orders from the SS. However, sharing work and functioning as a team is encouraged, but the supervisor should keep enough distance to maintain an overview of the situation. Again, this episode is an example of proactive action to manage performance variability in the face of adversity and pressure, to keep the system under control.

Episode 5: Leadership-style and context mismatch

There did not appear to be explicit changes in the mode of operation in the crew performance summaries analysed above. However, expert observers recognised different styles of crew working which could be considered as different modes of operation between crews. We describe a case here where the success or failure was dependent upon the mode of operation in different scenarios. Interestingly, this shows that success and failure can come from the same source in complex systems.

Expert observers recognised two crews which were high performing across multiple scenarios. However, the different crews failed and excelled in two distinct scenarios. Crew A had a relatively novice Shift Supervisor (SS), an experienced team, and a very collaborative and reflective style. They excelled in Scenario X, where there was hidden complexity that was not obvious at the outset, but failed in Scenario Y that required fast and decisive action. In contrast, Crew B had an experienced and confident SS, a relatively inexperienced team, and a less collaborative style that centred around the decisiveness of the SS. Crew B failed in Scenario X and excelled in Scenario Y.

By using the model we can explain what happened with reference to the mode of operation and the strategies employed by the SS and crews. Crew A's implicit **mode of operation** was reflective; the **strategy** they used was critiquing situational models (i.e. questioning whether they understood what is happening properly); and the sorts of **observations** noted were team discussions and team meetings, whether in scenario X or Y. In contrast, Crew B's implicit **mode of operation** was decisiveness, the **strategy** they used was prioritizing tasks rather than reflecting on their interpretation, and the sorts of **observations** made were fast decisions and strong leadership, whether in scenario X or Y.

This episode of resilience is highlighted as being particularly interesting, as the mode of operation or leadership style cannot be judged as good or bad without reference to the requirements of the scenario, which are not known by the crews in advance. This is where positive resilience strategies in one scenario can be a vulnerability in another. This questions more normative notions of right and wrong behaviour; especially where complex interactions in practice are yet to play out and paths toward success and failure are masked.

6. Discussion

The framework presented in this paper offers a structure to make resilient observations at the small team level. This has been borne from the motivation to make resilience traceable from abstract theory to concrete observable manifestations; and to propose a shared analytic framework to facilitate resilience comparisons within and across domains. Studies that are too abstract are detached from the details of practice; and studies that are too specific are hard to generalise to other contexts and scenarios. The better prospect of comparisons within and across domains through a shared framework also increases the likelihood of studies building on one another rather than being a series of unconnected case studies that can be harder to draw together.

In our literature search, we found evidence for different parts of the framework, but we did not find a single source which brought together all of the elements. The framework was used to analyse the empirical data from nuclear control room operation. This gave a different perspective compared to the HRA methods that were used on the same data in the original study. One of the biggest differences was that most HRA methods aim to predict performance of an 'average crew', whereas our approach pays attention to specific interactions between operators, teams, resources, technology and the circumstances of the scenario. For example, the use of a paper clip as a cognitive resource by one crew is of little interest to an HRA analyst.

In terms of the practical use of the framework, we found domain expertise to interpret the data invaluable. For example, we found the analysis of the crew performance summaries was greatly aided by the process expert's commentary which was interspersed throughout the transcript of the crew's actions and the scenario's events. Here, the observers would sometimes note what they considered to be good or poor behaviour, e.g. 'good division of work', and more unusual behaviour, e.g. using the paper clip as a bookmark. These points would often be an indication of a resilience episode, which could then be analysed in terms of the elements of the framework, e.g. marker, strategies, observation, vulnerability, resource and enabling condition.

In the analysis, we also found that markers and strategies could be organised in different ways because the hierarchy was not set or clear but had overlapping categories. Given the maturity of the analysis, we did not let this hinder us, as we treated it as a semi-formal tool for understanding the resilience episodes rather than spending an excessive amount of time, at this stage, in debating the finer points of a marker, e.g. is 'maximising information extraction' a better marker than 'interruption management' for the strategy 'creating an external cue', and how are these markers related? Specific observations and vulnerabilities appeared the easiest elements to recognise in the data. From here, enabling conditions could be rationalised. During the analysis we found it difficult to identify modes of operation, but in retrospect these could manifest in different types of work; e.g. procedure-following modes, data-gathering modes, and problem-solving modes.

Future research should test this framework through a series of case studies. We believe a succession of case studies will provide the data for researchers to converge on an agreed set of markers and strategies for resilient systems. These markers and strategies might not be applicable within and across all domains, but it is exactly the potential for these sorts of comparisons that will allow such conclusions to be drawn. This paper has used resilience related literature, our experience in the London Ambulance Service and London Underground control rooms [e.g. 14, 23, 27], and data from the nuclear domain to support the framework. We plan to use this approach in the healthcare domain, and invite others to build on the work in their own areas.

The proposed framework has been developed and tested at the small team level. Future work should also explore the potential to expand the framework to guide assessment at the other levels in the markers approach i.e. individual, operational, plant and industry [24]. Since the framework is specific about its interacting parts, which is a development from more descriptive observational studies, it can be better scrutinised, developed and critiqued, in part or in whole.

7. Conclusion

The resilience perspective focuses on how the system responds to and compensates for poor behaviour, poor design, poor systems and poor circumstances when defence-in-depth is challenged and surprises happen. Our approach focuses more on what might be considered mundane and normal work, before anything goes wrong or errors occur. Where these positive behaviours remain implicit and invisible, they will not get the recognition they deserve, and at worst could be forgotten or designed away [1, 2].

This framework aims to be much more specific about recognising traceable markers, strategies, and observations of resilience; promotes grounding observations in data; and specifies important elements that affect resilience behaviour, e.g. mode of operations, resources and enabling conditions, vulnerabilities and opportunities. Being more specific about resilience behaviour should allow us to recognise where interventions can take place to assess or improve resilience in the system. We seek to analyse local strategies for resilience, how they interact with context specific factors, and how this affects performance outside design-basis. Once identified, strengths and weaknesses in system resilience can be attended to. For example, circumstances that facilitate the creation of new strategies in the repertoire can be created, and successful resilience strategies can be identified, enhanced, and shared within and across organisations.

Perhaps the most significant contribution is an attempt to create the conditions whereby resilient case studies can use a common framework for comparison and build on one another. Work still needs to be done on converging on a set of agreed markers and strategies; and the framework might need to be modified in the light of new arguments and empirical data. We see the proposed framework as a good first step toward a shared resource for resilience analysis, rather than a finished and prescriptive model. Contribution and critique are welcome so that case studies can be compared and built upon in a maturing field interested in resilience analysis.

Acknowledgments

We would like to thank Björn Johansson, Jonas Lundberg, and Erik Prytz for their engaging discussion at the resilience workshop, Pukeberg, Sweden, which contributed to ideas in this paper. Thanks also to the anonymous reviewer's comments that have helped the presentation of the paper. Furniss was part funded by the Institute for Energy Technology, Norway, and EPSRC grants EP/G004560/1 and EP/G059063/1. Back was funded by EPSRC grants EP/G004560/1 and EP/G059063/1.

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