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On the Resilience of Socio-technical Systems

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Abstract

When designing or redesigning socio-technical systems, it is often required that those systems be more ‘resilient’ as a result. However, exactly what is meant by resilience in these contexts is unclear. To design resilient systems, we must first be able to answer a number of questions, including: Should a resilient system change to accommodate influences or stay the same? If the system changes, where should this change take place? How do we decide which system, or sub-system, to make resilient? For any given system, answering these questions requires engagement with different stakeholders, allowing a conversation to take place that typically spans different disciplines. However, resilience is a difficult concept to communicate about because terminology is not used consistently across, or even within, domains. This presents a challenge for designers wishing to elicit or understand stakeholders’ requirements for the systems that they are concerned with. To address this, we conducted a workshop with stakeholders working in different areas of academia, industry and policy who are concerned with the resilience of socio-technical systems. The aim of this workshop was to identify what stakeholders might want to convey about resilience and what would help them to communicate effectively. We identified three main characteristics of resilience and three system features that are critical to communication about resilience. These are all illustrated with a diagrammatic framework that was developed from real system examples given by the participants. From the data we propose a set of distinctions that offer a starting point for discussions about resilience with diverse stakeholders.

Introduction

The world we live in is increasingly complex, interconnected and unpredictable. We face social and technological challenges, which must be overcome through the maintenance and redesign of existing systems, as well as the design and integration of new systems. Each of these systems has stakeholders at different levels and across domains, from those governing societies, to technical experts working on well-defined tasks. These stakeholders generally want their system to survive, or even thrive, in the face of uncertainty and unexpected influences. To describe this desire, people, from politicians to CEOs, use the word *resilience*.

The concept of resilience is difficult to talk about because it is really an umbrella term for a set of complicated ideas about change. The exact meaning of ‘resilience’ is not clear

and the term is used inconsistently across, and even within, domains. Not only this, but it is applied in contexts where we face systemic challenges, with technical and social systems that are increasingly interconnected. Socio-technical systems are designed to fulfil a specific purpose at the point they are first implemented, but are also expected to perform well in the future as legacy systems, despite the fact that they change and their environments change. These systems are also made up of parts that have been designed as well as parts that have evolved. This increases complexity and leads to emergent system behaviour, which makes it difficult to predict how a system will respond to influences.

A complex socio-technical system has many stakeholders. Each of these stakeholders will have a unique perspective on that system, which may be framed by various factors such as their domain of expertise, job role, and personal values. However, no single stakeholder can understand the system in its entirety. To better understand how resilience is interpreted and how it might be communicated, we held an interdisciplinary workshop with experts concerned with the resilience of socio-technical systems. The participants discussed the resilience of a broad range of systems, at various levels of abstraction and from different disciplinary perspectives. In the workshop, knowledge was transferred across domain boundaries and we observed the commonalities and differences between how the stakeholders communicated about resilience. To understand and represent the data, we also developed a diagrammatic framework, which can be used to illustrate examples of resilience. This chapter reports on that workshop, proposing a set of resilience characteristics and system identifiers that offer a starting point for discussions about resilience with diverse stakeholders.

To present the findings of the workshop, the rest of the chapter is structured as follows. Firstly, we review the concept of resilience in the literature and relate it to systems principles. Then we introduce the workshop method. The findings are presented in three sections including: the development of the framework, the characteristics of resilience that are important in stakeholder discussions, and features of systems that are important to consider when clarifying resilience issues. The final section concludes the chapter by summarising the contributions of the workshop.

Background

To refer to the resilience of a system is to make some claim about the way that system responds to change, often a response that leaves the essential identity of the system intact. For example, a diversified public transportation system can demonstrate resilience by continuing to move people effectively around a region despite being influenced by severe weather, government policy and the expansion of the suburbs. Resilience is an important concept in many domains and is used to understand the behaviour of organisations (Sheffi and Rice 2005), cities (Campanella 2006), social-ecological systems (Folke et al. 2010) and socio-technical systems more broadly (Pavard et al. 2006).

Resilience is evidently a desirable property of many systems, but there is a lack of knowledge in the literature about how to design resilience into systems. This problem is exacerbated by confusion over the meaning of resilience and the different concepts that relate to it (de Weck et al. 2012; McManus et al. 2007; Ross 2008). This ambiguity makes it difficult to understand the requirements that are being placed on those who create and operate socio-technical systems and to account for the expectations of their clients or the

wider public. The problem is further complicated because systems can be viewed at different levels of abstraction, with one person's system viewed as another person's component or sub-system (Buede 2000). Stakeholders might be interested in sub-systems, or separate systems that interact with the main system in question; these other systems could be social, technical or some combination of the two. This means that there is confusion not only about what resilience is, but also about what it is that should be resilient and how. There is a lack of research looking at how these concepts are communicated in practice and therefore it is not clear what questions we should be asking system stakeholders about resilience, so that we can understand what they want and why.

The Concept of Resilience

The word resilience has long been used to refer to the way in which materials and structures rebound or recover from a disturbance. This term was first applied to a systems context in 1973 with Holling's now-seminal work on the resilience of ecological systems. Here, resilience was defined as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling 1973, p.14). Over time, the concept of resilience has gained traction across academic domains including disaster risk management (MacAskill and Guthrie 2014), community studies (Baek et al. 2015), economics (Simmie and Martin 2010), and psychology (Johnson et al. 2016). Although some authors make distinctions between resilience in different domains, for example engineering resilience as distinct from ecological resilience (Joseph 2013), these conceptual boundaries are increasingly blurred. Rather, resilience can be seen as encompassing a set of related ideas rather than a single concept (Westrum 2006).

Generally, the term resilience is used to describe how complex systems, whether naturally occurring or designed, can respond to adverse influences in order to survive, or thrive. There are two characteristics of resilience that are prominent in the literature: the ability of a system to resist by absorbing influences (Dovers and Handmer 1992; Holling 1973; Timmerman 1981) and the ability of a system to recover from influences (Pimm 1984; Timmerman 1981; Wildavsky 1988). Resisting and recovering are often seen as part of the same process that occurs when a resilient system is faced with an influence (Amalberti 2006; Cardona et al. 2003; Haimes et al. 2008). A system that is able to resist influences without changing in structure or function is described in some fields as robust (Chalupnik et al. 2013; Fricke and Schulz 2005; Ryan et al. 2012). However, when resilience is defined as a system's ability to recover, it is not clear if the system changes in function or structure in order to achieve that recovery.

In contrast to a general description of 'recovery' or 'bouncing back', some authors explicitly refer to the ability of a system to respond to influences by changing in structure or function. The idea of a resilient system being able to 'adjust' or 'adapt' appears in the literature in the late 1990s and offers two additional aspects of resilience: firstly that a resilient system can respond internally to influences (Comfort 1999; Haimes 2009; Home and Orr 1997; Maguire and Hagan 2007; Rose and Liao 2005; Woods and Cook 2006); secondly, that a resilient system can adopt a new state (i.e. undergo a structural or functional change) rather than recover to the previous state (Adger 2000; Carpenter et al. 2001; Fiksel 2006; Jen 2003; Kimhi and Shamai 2004; Smith and Violanti 2000; Pariès 2006; Simmie and Martin 2010; UN/ISDR 2004). This characteristic of resilience is related to the system lifecycle properties flexibility and adaptability (Chalupnik et al. 2013; Fricke and Schulz 2005; Ryan et al. 2012). The terms flexibility and adaptability are often used synonymously to describe all types of system changeability.

The question of how to describe resilience has been debated strongly in the literature. For example, some authors argue that the term is becoming too broad, to the extent that it can be meaningless (Joseph 2013; Rose 2007). One reason behind this, is that the term is used to describe different types of system facing different types of influences that operate at different levels within the system (Handmer and Dovers 1996; Westrum 2006). The conceptual breadth of resilience can also be seen in a more positive light, as a necessary reflection of the complexity of socio-technical systems. Using a single term across domains means that ostensibly different ideas in different fields of study can be shown to be essentially identical. In either case, we must have ways to talk about different types of resilience.

A Systems Approach to Resilience

The importance of a holistic approach to resilience is evident in the ecological and socio-ecological literatures. Here we make the case that the same is true in socio-technical systems. At a low level, it is desirable that technical systems are predictable, reliable and robust. For example, a car is designed to perform under a set of environmental conditions that have a predetermined range, such as temperature, road surface and impact forces. A car is designed to be efficient and cost effective. However, when a car is combined with a driver, the combined system can be resilient, dealing with unexpected external events. In this combined system, the car resists influences and the driver changes to accommodate influences. Engineers are generally adept at designing systems that resist or recover in response to influences. It is designing systems that change to accommodate influences that presents the greatest challenge. Some researchers have tried to address the challenge of designing changeable technical systems and found it necessary to take a socio-technical approach (Melese et al. 2016).

In both design literature and practice there has been increasing interest in the design challenges associated with socio-technical systems (Norman and Stappers 2015). These socio-technical systems, such as governance, healthcare and transportation, are often large and complex, spanning across domain boundaries. Their success is usually dependent on the interactions between technical and social sub-systems. Therefore, taking a systemic approach to the design of socio-technical systems can reveal insights about their structure and behaviour, which would not be apparent if looking at either the technical or social sub-systems in isolation (Behymer and Flach 2016). Some researchers insist that engineers and designers of technical systems have a moral obligation to consider the wider social systems that they design for or within (Vermaas et al. 2011). More generally in systems engineering, by expanding the boundaries of the technical systems we consider, most designed or engineered systems either contain or interact with a variety of people, organizations, economies, and other entities that are often best understood on a socio-technical basis (Kroes et al. 2006).

The socio-technical systems that stakeholders must analyse, understand, and improve are often partially designed and partially evolved (de Weck et al. 2011). This requires stakeholders to grapple with the complexity of systems that they only incompletely understand and to interpret emergent behaviour that was not anticipated (Chen and Crilly 2016a, 2016b; Frei and Serugendo 2011a, 2011b). The function and structure of such systems will be perspective dependent. That is, two stakeholders might view the same

system from a different level of abstraction, and only be aware of some of the social and technical sub-systems that are relevant at that level.

Relating Resilience to System Attributes

One way to understand resilience in the context of systems is to identify related attributes. These attributes can be built into systems in order to realise certain system lifecycle properties. These attributes can be designed into system architectures, which can be functional, physical, technical or dynamic operational (Levis 1999). Table 1 lists some of the attributes that have been linked by authors to increased system resilience in both technical and social systems. Other system attributes listed in the literature are either domain-specific, e.g. 'leadership' or 'trust' in social systems (Carpenter et al. 2012), or are some variation on the attributes listed in Table 1. For example, 'clustering' is described as the extent to which strongly connected components are grouped into distinct sub-systems, which can help to avoid the negative consequences of connectivity by containing the effects of influences to a single cluster (Ash and Newth 2007). This is a type of modularity. Similarly, 'degeneracy' is a form of functional redundancy where functions in a system can be redistributed amongst different system components (Whitacre and Bender 2010).

The amount that each attribute increases (or decreases) resilience is dependent on the system, the level within a system the attribute occurs, and the types of influence the system faces. It is not the case that increasing one system attribute will indefinitely increase the resilience of a system. McDonald (2006) describes some of the trade-offs between system attributes in the context of organisations, listing the apparent contradictions that must be resolved in a resilient organisation:

- Formal procedures – local autonomy of action;
- Centralisation – decentralisation of functions/knowledge/control;
- Maintaining system/organisation stability – capacity to change;
- Maintaining quality or product/service – adjust product service to demand or changing need;
- Use well-tested technologies – develop innovative technical systems.

Each point illustrates trade-offs between robustness (the first statement in each bullet point) and flexibility or adaptability (the second statement in each bullet point). Generally, we can say that certain system attributes lead to certain characteristics of resilience. However, these relationships are not straightforward. Also, it is not clear how to apply these theories in practice for socio-technical systems. The first step towards understanding these issues more clearly, is understanding how to communicate about resilience concepts.

Table 1: Attributes that contribute towards resilience in socio-technical systems. The diagrams show how a system might differ if it had more or less of the attribute in question.

ATTRIBUTE	DESCRIPTION	SYSTEM EXAMPLES		REFERENCES
		More of attribute	Less of attribute	
MODULARITY	The degree to which a system is segmented into parts or sub-systems that can be removed or recombined in a different way. There are many different types of modularity, however, many authors refer to modularity without defining the type. Modularity can enable the reconfiguration or replacement of parts of a system.			(Ash and Newth 2007; Baek et al. 2015; Carpenter et al. 2012; Chen and Crilly 2014)
REDUNDANCY	The presence of duplicate parts or sub-systems in a system that can take over from one another when necessary. Can be functional or structural. This offers a backup option in the event of failure or damage. Redundancy also takes the form of reserves within a system that enable it to recover. In systems that are optimised to perform specific functions, redundancy can be seen as expensive inefficiency.			(Baek et al. 2015; Biggs et al. 2012; Bruneau et al. 2003; Carpenter et al. 2012; Comfort 1994; Madni and Jackson 2009; Whitacre and Bender 2010)
DIVERSITY	The number of different types of components with different functions. Increased diversity provides opportunities for the system to change or pathways between components to change. Although uniformity can lower production and maintenance costs in systems.			(Baek et al. 2015; Biggs et al. 2012; Carpenter et al. 2012; Fiksel 2003)

CONNECTIVITY	The degree to which components in a system are connected to one another. Increased connectivity can lead to an increase of alternative pathways through a system. This means that influences or their effects can potentially be avoided. It can also lead to the propagation of influences through the system so more parts are affected. Also referred to as openness.			(Baek et al. 2015; Biggs et al. 2012; Carpenter et al. 2012; Fiksel 2003; Mosleh et al. 2016; Whitacre and Bender 2010)
DECENTRALISATION	The degree to which a system is controlled from multiple hubs within a system, as opposed to centralised, top-down control. This gives sub-systems some degree of autonomy and can increase the speed and accuracy of response to influences.			(Ash and Newth, 2007; Biggs et al. 2012; McDonald 2006)
FEEDBACK LOOPS	The level of feedback within a system to its constituent parts. This feedback means the system can learn from past events as well as monitor influences and responses.			(Biggs et al. 2012; Carpenter et al. 2012; Leveson et al. 2006)

Method and Participants

To explore questions about resilience, a workshop was organised by the Cambridge Engineering Design Centre (EDC) and the Cambridge Centre for Science and Policy (CSaP) in December 2014. The selected participants were 21 senior policy makers, academics and industry practitioners. Although from very different fields of expertise, the participants all worked on complex socio-technical systems and were concerned with how to make those systems more resilient.

The format of the workshop comprised two chaired discussions lasting two hours each. The first workshop began with short presentations by four participants from different domains, representing issues related to the resilience of cities, space systems, insurgent groups, and national security. These talks illustrated the broad applicability of resilience to different socio-technical systems, the different perspectives that can be taken on resilience and the conceptual and communicative challenges that result from efforts to describe resilience.

Because the workshop stakeholders came from a diverse set of domains, the majority of the discussion referred to systems in the abstract sense, enriched with domain-specific examples. Communication across domains was helped by both abstraction, which highlighted commonalities across apparently disparate systems, and exemplification, which made the stakeholders' points compelling and accessible. Therefore, in discussing the findings for this study, the examples are presented in both abstract and domain-specific forms.

Sample

Table 2 summarises the workshop stakeholders by field of study and whether they work primarily in academia, policy or industry (many stakeholders crossed these boundaries).

The participants were all concerned with specific socio-technical systems, but these were of very different kinds and different aspects of them were emphasised. For example, the participants discussed the performance of cities (P10), the capacity of industries (P20), the emotional state of professionals (P05) and the operation of insurgent groups (P19). Despite this diversity, strong connections could be observed between how these different systems are thought about and how their resilience is considered.

Data Collection and Analysis

The workshop was recorded and transcribed for analysis, supported by extensive notes taken by two independent observers. The resulting material was analysed and themes were drawn out relating to what the participants were communicating about resilience and the difficulties they had experienced in doing this. The themes arrived at were discussed between two researchers and compared against the notes and observations of other researchers present in the workshop (Robson 2011). This analysis process was supported by the development of a diagrammatic framework for representing resilience concepts, drawing together findings from the literature and the workshop data (Umoquit et al. 2013).

Table 2: List of workshop stakeholders by field of study or practice.

ID	FIELD OF STUDY/PRACTICE	ACADEMIA	POLICY	INDUSTRY
P01	Design Engineering	X		
P02	Human Geography	X		
P03	Operations Research	X		
P04	Mechanical Engineering	X		
P05	Psychophysiology	X		
P06	Biological Sciences	X		
P07	National Security	X	X	
P08	Science and Policy	X	X	
P09	International Politics	X	X	
P10	Science and Policy	X	X	
P11	Built Environment	X		X
P12	Architecture	X		X
P13	Telecommunications			X
P14	Architecture			X
P15	Space Systems			X
P16	International Policy		X	X
P17	International Affairs		X	X
P18	Healthcare Strategy		X	
P19	Counter Terrorism		X	
P20	National Security		X	
P21	Science and Policy		X	

The data was rich in examples given by the participants from their own experiences. Notable examples have been drawn out to illustrate the themes in this study. These are presented as abstracted system descriptions and diagrams, for domain neutrality, using the diagrammatic framework, before being given in the original domain-specific context. The domain-specific examples are paraphrased from the workshop data and are referred to with the Participant ID numbers (see Table 2). These participant numbers are also used in the text to indicate how the themes are connected to the data. The workshop was conducted under the Chatham House Rule (Chatham House 2017), therefore the identity and affiliations of the participants are not given. The examples given are not direct quotes from any individual but were derived from analysing the discussions between participants.

Analysing the data revealed what stakeholders are trying to communicate when they talk about resilience. The data also suggested ways in which communication about resilience can be improved. The issues raised in the workshop are enriched with real life examples from the stakeholders' own experiences. These examples are developed from the workshop transcript and used to illustrate each abstract system example.

Developing a Diagrammatic Framework for Resilience

To represent and abstract the system examples that the stakeholders gave in the workshop, we developed a diagrammatic framework. This is based on the findings from the workshop, on what needs to be communicated about resilience, and is informed by the academic literature, on how to represent resilience concepts. In the literature, diagrams already have been used to communicate to an academic audience, however no existing diagrams were available for capturing resilience discussions between system stakeholders or for communicating across different domains. Our diagrammatic framework was developed to fulfil those two functions.

System Structure

The structural aspects of the framework are shown in Figure 1. Stimuli that influence a system are shown on the left of the diagram. In engineering systems, *exogenous influences* typically include natural environmental or financial conditions, whereas *endogenous influences* could be component failures or emergent behaviour within the system (Crilly 2013). Separate from the stimulus, is the response shown on the right of the diagram. Changes in the system occur if there is an *exogenous change agent*, which could be a consultable client in a project or a system operator, or an *endogenous change agent*, such as an automated mechanical response.

Figure 1: Hierarchical graphical representation of a system showing stimulus and response.

The system structure is shown using three levels of abstraction: *system*, *super-system* and *sub-system*. This hierarchy allows changeability to be discussed with stakeholders at different system levels. For example, in the case of achieving a robust system by designing flexible and adaptable sub-systems. In practice the system boundary and level of abstraction will be decided by specific stakeholders depending on their individual perspectives (Maier and Rechtin 2009).

A set of lifecycle properties based on the structural aspects of the framework is shown in Table 3. This set was formulated using permutations of stimuli and responses alongside the linguistic definitions in the literature. Lifecycle property names have been suggested although, as in the literature, not all stakeholders may share common definitions. As such, we focus here on the varieties of lifecycle properties that might be distinguished and represented, rather than the labelling of those properties. Efforts have been made to consider specific lifecycle properties discussed in this research but it is not claimed that the diagrams presented are exhaustive or definitive; they are a starting point for discussion.

Table 3: Framework for structural representations of system lifecycle properties.

<p>An exogenous influence stimulates the system but there is no response. The value delivery may improve or degrade but remains within the acceptable threshold values. The form or structure of the sub-systems may change. This is commonly referred to as <i>robustness</i>.</p>
<p>An exogenous influence affects the system. An external change agent responds to the influence, enabling a system change. This is referred to as <i>flexibility</i>.</p>
<p>As above, an external change agent enables system change but the influence in this case is endogenous. This is also considered to be <i>flexibility</i>. Although a distinction is not generally made between the two cases, it may be useful to do so.</p>
<p>In this instance, an exogenous influence initiates a response from an internal change agent. The change agent enables a system change. This is generally called <i>adaptability</i>.</p>
<p>As above but with an endogenous influence. Also referred to as <i>adaptability</i>.</p>

System Function

The functional perspective in the framework allows us to show how the system's purpose, role or identity changes over time. This is achieved by using a temporal arrow, which represents the function of the system. The arrow can be used to show situations where for example, a flexible or adaptable system responds to an influence and redefines the value delivery of the system to meet new challenges. There are three main paths the function arrow can take in response to an influence: the value delivery does not change (Figure 2a), the value delivery changes temporarily (Figure 2b) or the value delivery changes permanently (Figure 2c).

Figure 2: Arrows showing the function of the system progressing through time as the system (a) resists an influence, (b) recovers from an influence and (c) changes in response to an influence.

Combined Framework

Representing both the structural and functional aspects of changeability can be done using the combined framework shown in Figure 3. The system function is shown as an arrow representing the system progressing through time. The structure of the system can be shown at snapshots in time, at the points where representing the structure is most helpful or when that structure is known (assuming that in a complex system the structure will sometimes be unknown).

Figure 3: Combined framework showing the system structure and function.

How People Talk about Resilience

None of the participants offered formal definitions of resilience in the workshop but particular interpretations of resilience were implicit in what they said. Generally, these notions of resilience related to how a system responds to influences in order to continue functioning. However, as shown in the literature review, resilience is not a standalone concept but instead encompasses a group of system lifecycle properties that relate to both persistence and change. By combining these properties in different ways, three main characteristics of resilience emerged in the workshop:

- R1: Resilience as resisting influences
- R2: Resilience as recovering from influences
- R3: Resilience as changing to accommodate influences

These characteristics of resilience represent the variety of perspectives on resilience discussed in the workshop, rather than a consensus view. Some participants referred to a single characteristic, whereas others saw resilience as encompassing two or more characteristics. Significantly, these characteristics appear to cover all of the various interpretations of resilience in the literature.

Resisting Influences (R1)

The workshop participants considered the system's ability to resist influences as a marker of resilience, reducing the initial impact of an influence or the fragility of the system (P11, P14, P21). The literature review suggests that this characteristic is equivalent to the system lifecycle property robustness. However, as shown in Example 1, an over-emphasis on system robustness can lead to missed opportunities.

Example 1: System X is influenced by system Y. System X can (a) resist the influence and remain unchanged or (b) change to accommodate system Y. In the latter case, the structure and function of system X may change.

Example 1 in the context of social sciences: (a) A society (X) sees a group of new people (Y) as a threat to their collective identity so they protect themselves, refusing to let the

group become part of their society and resisting change. Is the society being resilient or are they rigid? (P09).

Figure 4: Diagram showing system X (a) resisting the influence of system Y and (b) changing to accommodate system Y as a new subsystem.

In Example 1, system X could represent a society that resists changing to accept incoming people (Figure 4a), which can be seen as rigidity rather than resilience. A society that welcomes new people has the potential to increase the functionality of the system, even though it might change the 'purpose' of the society (Figure 4b). The ability to resist change (to be robust) is an important characteristic of resilience, but it is not always desirable. Increasing robustness without considering other aspects of resilience, such as the ability to change to accommodate influences (R3), does not just risk the system becoming rigid, it may also make the system fragile.

To increase the ability of a system to resist influences there are two possible approaches: to make things harder to influence or to reduce the impact of influences. The first of these can be achieved by being impenetrable to outsiders who could potentially influence the system (P19). Alternatively, the impact of influences can be reduced or absorbed by strengthening a specific part of the system (P06, P14, P20), for example by making the nodes of a network robust (P20). This selective robustness is preferable to the whole system being robust and therefore rigid. It is also likely that only some of the system is well understood or accessible, for example, resource flows may be easy to disrupt whereas physical entities are easier to make robust (P20). Having some vulnerable system components means that small breakages can occur, which allow for change, preventing stress building up in the system until it reaches a tipping point where the system suffers catastrophic damage (P06).

Recovering from Influences (R2)

A robust system may decrease in performance after being subjected to an influence. For example if an influence reduces functionality temporarily, once that influence is removed, the system may be able to resume normal functionality and recover to previous performance levels. This type of recovery, where the system does not change but has the capacity to recover, can be considered part of robustness. At a certain level of abstraction, the recovery process will not be observable and the system will appear to be robust having apparently not changed in structure or function. Equally, some observers will not be able to see there has been any performance loss.

There is however another type of recovery where the structure and function of a system change in response to an influence, but eventually return to the original functions and

value-delivery. Example 2 shows how during this period of change the system survives by temporarily changing its value delivery.

Example 2: System X has two purposes (P1 and P2), which, at the beginning ($t = 0$), can be fulfilled simultaneously by the system. When the system is affected by an influence (I), it adapts to focus system resources on fulfilling one purpose, P2. Once the influence is no longer affecting the system, the system recovers to resume its previous state, fulfilling both P1 and P2.

Example 2 in the context of psychophysiology: An athlete (X) must sustain two purposes to be successful – mental wellbeing (P1) and high levels of physical performance (P2). In a bid to maintain their physical performance during a competitive sports event (I), an athlete's mental performance can suffer. Does a resilient athlete maintain both their mental wellbeing and physical performance at all times, or have the capacity to recover? (P05)

Figure 5: Diagram showing Example 2, a system (X) that responds to an influence by temporarily fulfilling one purpose (P2). Once the influence is no longer affecting the system, the system recovers to the initial system state.

In this example, an athlete's mental wellbeing is temporarily affected by a competitive sports event but recovers after the influence. The system's athletic function is maintained (physical performance) because it is prioritised over other functions (mental wellbeing). The diagram in Figure 5 could represent a small section of the athlete's career. However, if an

observer was looking at the athlete at a higher level of abstraction, over a 20 year career, then these periods of recovery may be unnoticeable and the athlete would appear to be resisting influences.

If the system is observed at points in time before and after a recovery, the difference between robustness and recovery will not be observable. Similarly, if an observer can only see the section of time when the influence affects the system and not the recovery, then it may look like the system is adapting or flexing. Redundancy in the system can increase the speed of recovery because the core functions of the system can be performed by the redundant components (P20).

Changing to Accommodate Influences (R3)

Traditional design approaches, which focus on designing robust and performance optimised systems, will not necessarily result in resilient systems. These robust systems are able to tackle existing and predicted influences but can become rigid and fragile if faced with new and unexpected influences. To avoid this, a system must also have the capacity to change. Example 3 shows a system that is optimised for specific functions but this limits the possible changes that can be made in the future without breaking the whole system. Eventually when an unexpected event influences the system, the system cannot change in time and breaks down.

Example 3: System X consists of a set of components (C1 – C6). When an influence, I1, affects the system, the relationships between the components are constrained to make the system faster at responding to future influences of the same type. When a second influence (I2) of a different type damages one of the system components (C6), the system can no longer function.

Example 3 in the context of engineering: Some engineering systems are continuously developed to increase robustness but eventually they get to the point where they might fail. Engineers counter this by creating more and more ways to try and control the performance. How do you avoid encrusting the system with constraints and making it fragile? (P04)

Figure 6: Diagram of Example 3 showing a system (X) where the structure is optimised in light of the first influence (I1) to increase the system's robustness. When the system is influenced for the second time (I2), the structure of the system does not allow the system to change to accommodate the influence so the system fails.

Engineering systems often make use of newly available technologies, which can compound the problem illustrated in Example 3. The workshop participants thought that

the level of technology in the system did not increase resilience; some even thought that technological advancement decreased resilience (P16, P19). New technologies are unlikely to make systems more resilient if they are complex and not well understood or highly specialised and inflexible.

A complex system is inevitably linked to other systems and although this might make its behaviour hard to predict, it can increase the ability of the system to change (R3) by offering multiple ways to perform functions and the potential for new functions (P07). Similarly, a system that is vulnerable but resourceful can be said to be resilient, with the capacity to change to accommodate influences. This does not necessarily mean the system has an abundance of resources but that it can use what it has effectively, this was described by one participant as 'frugal innovation and adaptability' (P07). The ability to change effectively requires a balance between complexity and control. Although centralised control is an effective way to monitor and maintain a system, decentralised systems allow for bottom-up changes so they can adapt more easily and quickly to influences (P10, P18, P20). These approaches contrast with the principles of 'just-in-time' (P04). Just-in-time systems are well-resourced and operate comfortably under normal operational conditions. Resilient systems may be less well-resourced but are highly adaptable to unexpected influences.

How to Structure a Discussion about Resilience

Working from a systems viewpoint raises some important issues that occur when dealing with multiple stakeholders who have varying perspectives, working at different levels within a system. The workshop data showed three features of systems that must be defined to make communication easier: the system boundary, the system purpose and the stakeholder's perspective.

System Boundary

Whether a system is considered to be resilient or not may depend on where and how the system boundary is drawn. This is illustrated with Example 4, where the resilience of a system is determined by the definition of the boundary.

Example 4: System X consists of two sub-systems (X1 and X2). When an influence (I) affects system X, one sub-system survives (X1) but the other sub-system stops functioning (X2). System X2 is not resilient to the influence but systems X and X1 are resilient.

Example 4 in the context of biological sciences: *Staphylococcus aureus*, or SA, (system X) is a type of bacteria that is a common cause of infection, often treated with penicillin (I). However, over time some of these organisms have developed into Methicillin-resistant *Staphylococcus aureus* (MRSA). MRSA (X1) is not any more virulent than other SA organisms (X2) but is resistant to antibiotics such as penicillin. Can you say that SA is resilient or only that the subset of MRSA organisms is resilient? (P06)

Figure 7: Diagram of Example 4 showing the resilience of system X when affected by an influence (I).

The participant describing Example 4 in the context of a biological system defines the system as a species of bacteria ‘*Staphylococcus aureus*’, therefore the system is resistant (R1) to the influence of antibiotics. There is, however, degradation of the system in this case; some of the bacteria, those not resistant to the antibiotics, are destroyed by the antibiotics. If the system was defined excluding the resistant strain ‘MRSA’, then the system could not be called resilient because the whole system would be destroyed by the antibiotics.

Drawing a system boundary is not always straightforward. Sometimes it is unclear which system should be made resilient and sometimes a system cannot be clearly defined (P19). When different stakeholders talk about the resilience of a system, the system boundaries that they each draw may be different, reflecting their individual responsibilities and perspectives. Dividing a complex socio-technical system into component parts or events for analysis can be an overly simplistic approach as system resilience may have to be considered holistically (P18, P20).

System Purpose

Once the boundary is determined, it is important to be clear about what the purpose of the system is (these steps may not be sequential since the boundary could be defined based on the purpose that is being addressed). The purpose of the system should reflect the value that the system is delivering, the functions that the system performs or the identity that the system maintains. Resilience can then be defined by the ability of the system to maintain that purpose (P19). The importance of defining a purpose is shown in Example 2 in the context of psychophysiology. If the purpose of the athlete is not defined holistically, with the system boundary defined to include mental as well as physical performance, then their career could be short lived.

Example 2 (continued) in the context of psychophysiology: The ‘emotional resilience of an athlete’ could refer to at least two different things: the way a person (system X) maintains high levels of physical performance (P2) despite setbacks to their mental wellbeing (P1); or the way a person maintains high levels of mental wellbeing despite setbacks to their physical performance (the second case might be the reverse of the first case i.e. Figure 5 could represent both situations with the purposes, P1 and P2, reversed). Maintaining mental wellbeing may conflict with maintaining extreme levels of physical

performance. When someone says that an athlete is resilient, do they mean resilient in terms of performance or wellbeing? (P05)

Example 2 also highlights how different stakeholders may define the boundary and purpose of the system differently. The athlete might have a personal trainer who is trying to increase their physical resilience by controlling their exercise and nutrition, whereas a psychologist might prescribe rest and social interaction to improve the athlete's emotional resilience. If the purpose of the athlete is defined as maintaining a high level of performance over a period of 6 months for a particular event, then the emotional wellbeing of the person is likely to receive less investment than their physical health. If the athlete's purpose is to maintain their performance over a period of 20 years, then it is more likely that the available resources will be distributed more evenly to achieve both physical and mental resilience.

Once the boundary and purpose of relevant systems have been identified from the perspective of different stakeholders, the cost of resilience can be considered. In the workshop, cost was not necessarily seen as monetary but what the system, or the 'owner' of the system, has to give up in order to increase resilience (P03).

Level of System Abstraction

Although differences in stakeholders' perspectives can make defining resilience difficult, the usefulness of a variety of viewpoints, from multiple levels of abstraction, in socio-technical projects was also highlighted in the workshop. An emphasis was placed on the importance of decision makers being able to understand and benefit from the perspectives of their team (P10). This would be helped by the stakeholders being able to articulate how they are defining the system boundary and purpose. Example 5 shows how viewing a system from different levels of abstraction can lead to different approaches to resilience.

Example 5: System X is affected by an influence and divides into three separate systems (X1, X2 and X3). Defining the purpose of these systems is dependent on the perspective of the stakeholder. At a high enough level of abstraction, X1, X2 and X3 might appear to have the same purpose, P1, which encompasses P2 and P3.

Figure 8: Diagram showing Example 5, a system splitting into three groups fulfilling different sets of functions.

Example 5 in the context of human geography: An island community was facing environmental threats in the area where they lived. Some of the people stayed in the area

(X2), some moved to a new area of the island (X1), and others left to live in a new country (X3). These groups fulfil different purposes: living as a community (P1), living as a community anywhere on the island (P2) and living as a community in the original area of the island (P3). Which group of people are most resilient? (P02)

In the human geography example above, all three groups of islanders could be considered resilient depending on the perspective of the observer. The islanders who stayed in the dangerous area considered themselves resilient, resisting and recovering from environmental forces and adapting their infrastructure (P02). Those who moved to another country did not consider themselves resilient because from the islanders' perspective, the value of their community is inherently linked to the area on the island that they came from. However, the researcher, as an outside observer, saw the group who moved away as most resilient, adapting to a new culture and thriving as an ethnic community in a new country (P02). Whether each of these different groups is resilient depends on what essential features define the group: being in a specific area, being on a specific island or just being a community.

Stakeholders who are within the boundary of the system may not be able to abstract and look at the system from an outsiders' perspective. Equally, an outside observer may not be able to understand the perspective of those acting within the system. As a result, these different people may declare the same apparent system to be or not be resilient depending on the perspective they adopt, the level of abstraction they view the system from, and the values they hold.

Summary and Conclusions

Socio-technical systems are complex, interconnected and have emergent properties. Just as the system boundary might be hard to define, there are often 'black boxes' in systems that might be measurable under normal operational conditions but still not be fully understood (P15). Current design methods often assume a reducible, controllable system but this is usually far from the truth. In practice, systems are modelled and simulated based on assumptions so that when a system is affected by influences that contradict those assumptions it can behave in unexpected ways. To compound this, understanding the perspectives of other stakeholders is not trivial.

Drawing together policy makers, industry practitioners and academics from across domains has demonstrated how many of the same issues arise in apparently disparate systems. The main barriers to understanding resilience are the ambiguity of the terminology and the lack of tools available to communicate this multifaceted concept. Three characteristics of resilience emerged from the workshop data, which are consistent with definitions of resilience in the literature: resilience as resisting influences (R1), resilience as recovering from influences (R2) and resilience as changing to accommodate influences (R3). This combination of resist, recover and change was identified as a strong defensive design strategy for both prevention (to minimise the effects of an influence) and exploitation (to take advantage of new opportunities). A resilient socio-technical system is likely to have components that collectively possess all three of these characteristics. However, understanding of the third aspect, related to system flexibility and adaptability, is underdeveloped both in the literature and in practice and therefore the most difficult concept to communicate.

It is necessary to look at resilience, and system changes, in the context of time. In the system lifecycle property literature, this is dealt with by showing systems responding to stimuli over time (Nachtwey et al. 2009). Considering system behaviour over longer time periods represents new challenges compared to static analyses used in fields such as robustness engineering (Fitzgerald and Ross 2012). The notion of time and change over time

is evident in many of the system examples presented here. However, the stakeholders tended to represent systems at discrete intervals, talking about a system before and after an influence. This can be misleading. For example, a system that recovers from an influence over a period of a year may appear the same at the start and end of that year. However, in the middle of the year that system's structure and functions could be very different.

In addition to resilience possessing different characteristics, much of the confusion that surrounds discussions of resilience can be attributed to uncertainty over three different features of systems: the system boundary, the system purpose and the stakeholder perspective. The diagrammatic framework developed in this study encourages the definition of a system boundary and purpose, making perspectives on the system explicit. This is particularly important in identifying cross-scale interactions in socio-technical systems, building on and extending work in the ecological and social sciences on the concept of panarchy (Allen et al. 2014). This framework also provides a foundation to explore how to communicate resilience with stakeholders who may not be as familiar with the concept as the participants of the workshop.

There are very few discussions of system abstraction in the literature, although there is some representation of lifecycle properties mapped to levels of abstraction in a manufacturing system (Wiendahl et al. 2007). On the other hand, there is a strong emphasis on the importance of defining system boundaries, with the aim that system influences and responses can be shown relative to the system boundary (de Weck et al. 2007; Haberfellner and de Weck 2005; McManus et al. 2007). This study confirmed that defining a system boundary is an essential step when understanding and talking about resilience. Currently the literature focuses on resilience and changeability for a given system at a given level of abstraction. Looking across levels of abstraction leads to new insights about resilience. For example, a single technical system might appear fixed from the perspective of a stakeholder operating at a managerial level, but it might appear changeable to a technical expert.

In this research, purpose emerged as a core theme. Identifying the purpose of a system tells us about the nature and function of that system as well as the perspectives of its stakeholders. However, some systems are perceived by stakeholders as not having a 'purpose', rather they just exist. This raises an important distinction between the study reported here and the ecology literature. We have taken the stance of treating resilience as a multi-faceted concept, arguing that resilience should be treated as a cross-domain concept rather than, for example, treating ecological resilience as fundamentally different to engineering resilience. However, for the most part, the social and technical systems discussed by the participants are human constructs, designed by and for people. Even in cases where these systems are autonomous and evolving, they were created with some purpose in mind. It is unclear how this work could be applied to systems without a definable purpose. This includes some large social systems and ecological systems. Although, as with much of this work, purpose is perspective-dependent so there might be cases even for ecological systems where certain stakeholders can define a purpose for that system. For example, taking the city example in the quote above, a mayor might have a very clear purpose or vision for their city, so applying the systemic approach developed in this research could still be of use.

Resilience is an important concept in the specification, implementation, monitoring and maintenance of many sociotechnical systems. However, discussions about resilience are hampered by confusion and ambiguity, especially when different stakeholders are

representing different systems or different aspects of the same system. By bringing a diverse group of system stakeholders together, opportunities were explored for increasing clarity about resilience. Collecting accounts of resilience in real world systems brings richness and tangibility to a topic that can often be vague and ill-defined. This can provide a useful basis for engaging with system stakeholders during design, offering ways to record their perspectives and ways to structure and communicate those perspectives to others.

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