Change or be changed: understanding resilience in socio-technical systems

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To Nerissa, for her resilience.

Abstract

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*.

Resilience is a term that is referred to across domains in academic and public discourse. However, the exact definition of resilience is elusive, and it is not clear how to apply resilience in the context of socio-technical systems. To design resilient systems, we must first be able to answer questions including: Does 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 and at what level of abstraction? In this research I show how we can answer these questions by eliciting, combining and contrasting the perspectives of multiple stakeholders of socio-technical systems. In order to talk to these stakeholders, in interviews and workshops, I had to overcome communication barriers.

Communicating about resilience is challenging because the term means different things to different people, both within and across domains. In this research I use diagrams to develop our understanding of resilience as a concept, prompt discussions with stakeholders, represent examples of resilience, and compare stakeholder perspectives across domains. Using these diagrams, I present three characteristics of resilience that have emerged from the literature and empirical studies: resisting, recovering and changing in response to influences. I also show how resilience is framed by stakeholders' perspectives and depends on how a system's boundary, purpose and timescale is defined. The characteristics of resilience are related to system dimensions, structure and function, with a focus on the similarities and differences between social and technical sub-systems. This research contributes a new understanding of resilience in the context of design practice, which moves us closer towards being able to design resilient socio-technical systems.

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Although they cannot be named individually, I am incredibly grateful to all of the stakeholders who gave up their time to participate in this research.

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Preface

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. It does not exceed the prescribed word limit for the relevant Degree Committee.

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Elements of this work have previously been published or submitted in collaboration, specifically:

Sections 2 & 5.2: Taysom, E., & Crilly, N. (2014). Diagrammatic representation of system lifecycle properties. In *Proceedings of the 4th International Engineering Systems Symposium (CESUN 2014).* Hoboken, NJ.

Chapter 5: Taysom, E., & Crilly, N. (under review). Interdisciplinary perspectives on resilience. In P. Jones (Ed.), *Systemic Design.*

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1 Introduction

Resilience is a word that embodies the time we are living in. As individuals and societal groups we face unexpected influences and threats such as political unrest, environmental disasters and new technologies. Fundamental shifts are taking place, in the way we travel, communicate and consume goods. However, it could be argued that this has always been the case. Over the course of history people have had to respond – whether gradually or suddenly – to the events around them. These responses can include design interventions, changes to an existing system or the design of a new one. What makes this period in our history unique, is that our world is more fast-paced and interconnected than it has ever been before. This means that it is harder to understand or measure the full impact of an individual's or societal group's design choices. It also means that the division between 'social' systems and 'technical' systems is not always clear. In most, if not all, cases we are designing within partially designed, partially evolved socio-technical systems. These boundaries will become increasingly blurred as the rise of machine learning and artificial intelligence mean that technology can make autonomous decisions previously reserved for humans. But the choices we make about if, when and how to respond to influences impact our ability to survive or thrive.

From politicians to CEOs, people use the word resilience to describe their desire to overcome challenges, bounce back from failure, and persist in the face of threats. However, the exact meaning of 'resilience' is not clear. At one point in this research I was in a workshop[1], where a group of system stakeholders, experts in policy, industry and academia, were discussing resilience. One stakeholder remarked:

> *'I think it was Humpty Dumpty who said, 'when I use a word I mean it to mean precisely what I mean it to be'[2]. We are using this word resilience in different ways, so I'm not going to use the word, I'm going to tell a bit of history and you can tell me whether it's relevant.'*

This thesis accepts that definitions of resilience will never be consistent across domains. Instead it takes stakeholders' stories and experiences and uses them to understand more about resilience in

[1] This workshop is detailed in Chapter 5.

[2] "When I use a word," Humpty Dumpty said in rather a scornful tone. "It means just what I choose it to mean – neither more or less."
"The question is," said Alice, "whether you can make words mean so many different things."
"The question is," said Humpty Dumpty, "which is to be master - that's all."
– *Through the Looking-Glass, Lewis Carroll (1871).*

systems. I have facilitated conversations, learnt how to talk about resilience, and used this learning to further our understanding of the concept itself. After all, if we cannot talk about resilience in a structured way, what hope do we have of designing resilient systems?

The concept of resilience is difficult to talk about because it is really an umbrella term for a set of complicated ideas about change. Not only this, but it is applied in contexts where we face systemic challenges, with technical and social systems that are increasingly interconnected. These 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. However, stakeholders are dealing with socio-technical systems that are 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. At one point in this research, a stakeholder, who worked in government, illustrated how the concept of resilience quickly becomes complicated when applied in practice:

> *'When I first started working in government, I was told resilience was response and recovery. You wanted to be prepared for an emergency in order to be able to respond well to it, and fast. But, in the 2007 flooding[3], in various parts of the country, the infrastructure was falling over, despite the fact that we had planned for it. That's when we discovered that resilience was a lot more complicated that we previously thought. It was complicated because just about everything was linked to everything else.'*

This complexity means that the specification, implementation, monitoring and maintenance of these systems requires diverse stakeholders from different domains to work together, applying design principles from multiple disciplines. Throughout this research I have tried to ensure that the stakeholders I have talked to in each study cross domain boundaries and levels of abstraction, from leaders of large organisations to experts in specific technical fields. This approach has not only lead to new insights, but also means that the contributions made to understanding and communicating about resilience, should translate into design practice.

[3] Reference to a series of floods that occurred across the UK in 2007.

Initially, this research's scope was limited to looking at how technical systems contribute to the resilience of socio-technical systems. I thought that if you could design technical systems that are resilient, the socio-technical systems that they are part of would be more resilient by default. Through the conversations I started having with stakeholders, it quickly became apparent that, even if the logic of technical resilience leading to socio-technical resilience was valid, I was at risk of overlooking an important insight: the greatest potential for resilience lies at the intersection between people and technology. It can be tempting to design humans 'out' of technical systems, particularly if those systems are complex. However, as one participant said, even in safety critical, high-risk environments like space operations, the role that people play in resilience should be capitalised on, not ignored:

> *'I'm interested in resilience in space operations. In these operations, not all system components are tractable, there are many black boxes. They also have very idiosyncratic bespoke missions. The systems have to be tweaked constantly and also monitored.*
>
> *There is the view of the operator as the one who presses the wrong button in an otherwise perfectly safe system. They think that the human is a liability that can 'ruin' things. But, the operator is not an error-machine. Instead they support the system, hacking it to make it more resilient. How do we increase this sort of resilience?'*

The challenge with this socio-technical approach is that people are complex systems even as individuals. Adding humans into a system increases the overall complexity to a degree matched only by the very latest developments in software systems. Software systems that promise to add autonomy, intelligence and therefore complexity. This requires a research approach that puts people at the centre of resilience research, gaining new understanding from stakeholders, as individuals and a collective group, about what resilience means and, ultimately, how to design for it.

1.1 Resilience in public discourse

One way to get a sense of what resilience means is by looking at what people have said on social networks over the last three years of this research. Figure 1-1 shows a word cloud created from the top Twitter tweets containing 'resilience' or 'resilient' and 'system' or 'systems'. Each word is scaled by area to show how often it appears across all of the tweets.

Figure 1-1: Word cloud of Twitter search results generated on http://www.wordle.net/. Search was conducted on 14th November 2016 on Twitter.com for tweets containing 'resilience' or 'resilient' and 'system' or 'systems' between the dates 1st October 2013 and 1st October 2016. 237 results were returned. Words are shown weighted and ordered by frequency across all tweets. Unrelated words, such as names of people and nonsense words, were not included in word cloud. The top 99 words are shown in the Figure.

From Figure 1-1 we can see that people talk about resilience in relation to the threats they face (e.g. 'ebola', 'climate', 'disaster'), change over time ('change', 'time', 'improve'), and the structure of systems ('complex', 'distributed', 'systems-of-systems'). The systems that are most talked about on Twitter in the context of resilience are large, complex, global networks that serve fundamental human needs, such as food, health and energy systems. These systems transcend domain boundaries but all have people at their core, with references to 'people', 'community' and 'human'.

Intuitively it makes sense that people would be at the centre of a discussion about resilience. Even as individuals, people have a remarkable capacity to deal with unexpected influences, from natural disasters to personal illness. What is less clear is where technology fits into this discourse. These systems, for food, health and energy, are enabled and developed using technology. For example, buildings to house organisations, digital infrastructure to document or communicate work, and global transport networks to distribute goods. The word 'technology' does not feature in Figure 1-1 but the prominence of words like 'design' and 'build' suggests that people are thinking about how to design resilience into these systems. Technology must be an important part of this conversation; it seems unlikely that a resilient health system could be designed without considering the design of technical systems like diagnosis equipment, patient admissions, and emergency transport. To understand the concepts that are central to resilience, such as the structure of resilient systems and how these systems change over time, we must first be able to talk about both the social and technical elements in these systems.

1.2 Stakeholder perspectives on complex systems

Complex socio-technical systems have many stakeholders. Each of these stakeholders will have a unique perspective of the system, which may be framed by various factors such as their domain of expertise, job role, and personal values. However, no one stakeholder can understand the system in its entirety. This research was conducted under the assumption that if we can understand the perspectives of individual system stakeholders, then we can gain a greater understanding of that system, and its resilience, as a whole. It was also assumed that incorporating these multiple stakeholder perspectives into our understanding of resilience is important because, before we can design resilient systems, these stakeholders must first be able to communicate about resilience in a way that prompts useful conversations, design ideas and subsequent innovation. Therefore, the main research question in this thesis is:

What can we understand about resilience from talking to system stakeholders?

In this question the 'we' refers to academics across different fields of practice who research resilience as well as practitioners who work in industry or policy and want to design for resilience. There are two challenges that must be overcome in order to answer this question. The first is, how do we talk about resilience when it is such a broad-ranging, ill-defined concept? The second is, how do we compare the perspectives of stakeholders who are looking at the system from different levels of abstraction and from different domains? These challenges are overcome, not with quantitative analysis, nor even definitive definitions of terminology, but by giving practitioners the tools to talk about their experiences, framed by their knowledge of the system. As such, this research provides a framework for communications between social and technical system stakeholders as well as between academics and practitioners. To develop such a framework, the concept of resilience must be decomposed into distinct elements that could apply to any type of system and will help us to structure a conversation about resilience.

The first step in developing an understanding of resilience in socio-technical systems was to review the academic literature on resilience and related concepts (Chapter 2). This learning could then be used to design a series of studies with stakeholders (Chapter 3). The first of these studies consisted of exploratory interviews with stakeholders of technical systems to understand how and why technical systems are designed to change or not change (Chapter 4). It was found that these stakeholders had not thought about the relationship between change and resilience and so it was difficult to talk about many of the issues surrounding resilience. Therefore the second study was orientated around a discussion between stakeholders who were already interested in resilience and were applying resilience concepts in their work (Chapter 5). This took the form of a workshop where these cross-domain stakeholders discussed resilience, comparing real world examples and discussing the challenges they faced. The final study in this thesis took all of the learning from the academic literature and previous studies and applied it in a case study with multiple stakeholders of the same socio-technical system (Chapter 6). The findings from the previous two studies were used to develop a system mapping exercise, which helped me to communicate with diverse stakeholders and draw comparisons across domain boundaries. In the discussion (Chapter 7), the study findings are compiled and related back to the literature to draw conclusions (Chapter 8) about what we can understand about resilience from talking to system stakeholders. As such, this thesis results from an iterative process of gaining understanding about resilience, then structuring this understanding to communicate about resilience, before using this structure to gain further insights.

2 Literature review

The literature approaches resilience from two broad perspectives. The first of these looks at resilience in much the same way as it is talked about in public discourse: in the context of specific domains and influences. For example, the resilience of our health system under the threat of an epidemic virus. The second approach is to look at resilience as one of a set of concepts called *system lifecycle properties*. These properties are generally discussed in the context of complex technical systems and relate to how systems can, or cannot, respond to influences through their lifecycle. Both of these approaches are useful when considering how to talk to diverse stakeholders about resilience. The first approach helps us to understand the characteristics of resilience across domains. The second approach helps us to decompose and abstract the important concepts that lie behind the system lifecycle property terminology, relating to system structures and functions. By distinguishing and relating resilience with other system lifecycle properties, I have developed a broader view of resilience concepts that can be applied across socio-technical systems.

In the first half of this review (Section 2.1) I included literature from a broad range of fields. This has helped me to understand different characteristics of resilience and identify which of these characteristics are used universally across different types of system (for example see Table 2-1). For this research, looking across academic fields is particularly important when trying to define resilience because different people, both academics and practitioners, will view the resilience of a socio-technical system with the lens of their domain background. When looking at what resilience means I found two limitations. The first is that the concept of resilience is often looked at retrospectively to describe how a system has responded to past influences. The second is that the concept of system change was underdeveloped in the literature. I wanted to develop our understanding of resilience by taking a prospective view of resilience and look at how changeability can be designed into system. Therefore, I needed a way to communicate about resilience in a way that was prospective and included discussions about change. To achieve this, in the second half of this review (Section 2.2), I focused more narrowly on one area of literature that would help overcome both of these limitations, the system lifecycle property literature from the field of systems engineering.

2.1 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, p14). Over time, the concept of resilience has gained traction across academic domains including disaster risk management (MacAskill & Guthrie, 2014), community studies (Baek, Meroni, & Manzini, 2015), economics (Simmie & Martin, 2010), and psychology (Johnson, Panagioti, Bass, Ramsey, & Harrison, 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 & 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, Crowther, & Horowitz, 2008). A system that is able to resist influences without changing in structure or function is described in some fields as *robust* (Chalupnik, Wynn, & Clarkson, 2013; Fricke & Schulz, 2005; Ryan, Jacques, & Colombi, 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 & Orr, 1997; Maguire & Hagan, 2007; Rose & Liao, 2005;

Woods & 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, Walker, Anderies, & Abel, 2001; Fiksel, 2006; Jen, 2003; Kimhi & Shamai, 2004; Smith & Violanti, 2000; Pariès, 2006; Simmie & Martin, 2010; UN/ISDR, 2004). This characteristic of resilience is related to the system lifecycle properties *flexibility* and *adaptability* (Chalupnik et al., 2013; Fricke & 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. 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 influence at different levels within the system (Handmer & 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 also means that ostensibly different ideas in different fields of study can be shown to be essentially similar ideas. In either case, we must have ways to talk about different types of resilience. One approach that some authors take is to break the concept of resilience down into sets of characteristics. Examples of these breakdowns are shown in Table 2-1. These characteristics have been sorted into columns to show conceptual similarities and differences between each authors' list.

Table 2-1: Table showing characteristics of resilience across domains.

	PREVENTION	IMPACT MINIMISATION	RECOVERY	INCREMENTAL CHANGE	ADAPTABILITY
SOCIETAL RESILIENCE (Dovers & Handmer, 1992)	'Resistance and maintenance'			'Change at the margins'	'Openness and adaptability'
SEISMIC RESILIENCE (Bruneau et al., 2003)	'Reduced failure probabilities'	'Reduced consequences from failures'	'Reduced time to recovery'		
SUPPLY CHAIN RESILIENCE (Ponomarov & Holcomb, 2009)	'Readiness and preparedness'		'Recovery or adjustment'		'Response and adaption'
ENGINEERING RESILIENCE (Westrum, 2006)	'The ability to prevent something bad from happening'	'The ability to prevent something bad from becoming worse'	'The ability to recover from something bad once it has happened'		

As can be seen from Table 2-1, the emphasis placed on certain resilience characteristics varies according to the field of study. This can be attributed to the difference in the purpose or identity of the types of system considered. Bharmra et al. (2011) compiled a list of resilience definitions across domains, which highlights these differences. For example, authors generally see the purpose of ecological systems as the preservation of living organisms, whereas, authors see the purpose of engineering systems as the fulfilment of specific clearly defined tasks. Holling (1996) describes this difference as follows:

> *'One definition [of resilience] focuses on efficiency, constancy, and predictability—all attributes at the core of engineers' desires for fail-safe design. The other focuses on persistence, change, and unpredictability—all attributes embraced and celebrated by biologists with an evolutionary perspective.'* (Holling, 1996)

In another domain, that of disaster and risk management, there is a focus on studying high impact, one-off events. There is an implication that for every hour that important parts of a system like a city are unable to function, people suffer and money is lost. Therefore in descriptions of resilience, the conceptual emphasis is placed on recovery and mitigation for future influences:

> *'[Resilience is] the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future [disasters]'* (Bruneau et al., 2003)

This domain effect is also evident in organisational resilience, (where the desire is to increase productivity and minimise variability), and psychology (where the desire is to increase personal capacity to bounce back from adversity) (Luthans, Vogelgesang, & Lester, 2006; McDonald, 2006).

Unifying domain-specific definitions of resilience is important because in practice the resilience of any one system will be affected, and to some extent determined, by the other types of systems that it interacts with. These interactions happen across domains, with the resilience of one type of system having the potential to negatively impact the resilience of another type of system (e.g. a thriving social community having a negative impact on an environmental ecosystem) (Adger, 2000). These interactions also happen across different levels of abstraction, with the resilience of a system at one scale influencing the resilience of a system at another scale (Woods, 2006).

2.1.1 Resilience in socio-technical systems

The importance of a holistic approach to resilience is evident in the ecological and socio-ecological literature. 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, Stikkelman, & Herder, 2016).

In both design literature and practice there has been increasing interest in the design challenges associated with socio-technical systems (Norman & 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 & 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, Kroes, van de Poel, Franssen, & Houkes, 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, Franssen, Poel, & Ottens, 2006).

The socio-technical systems that stakeholders must analyse, understand, and improve are often partially designed and partially evolved (de Weck, Roos, & Magee, 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 & Crilly, 2016a, 2016b, Frei & 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. In socio-technical systems theory, multiple levels of abstraction are grouped into three categories: 'primary work systems' (e.g. sub-systems of a whole organisation), 'whole organization systems' and 'macrosocial systems' (e.g. national institutions) (Trist, 1981). In this research, I use a similar approach to understand resilience in the context of a socio-technical system, combining individual stakeholder perspectives across different types of system and at different levels of abstraction.

2.1.2 Resilience as a system lifecycle property

To be able to gather the perspectives of stakeholders, we must have a structured way of talking about resilience in the context of socio-technical systems. Therefore, I have used work from the field of systems engineering, where researchers are exploring change concepts and relating them to system structures and functions. Here, resilience is one of a group of terms that are used to describe how systems respond to change and uncertainty, also including *robustness*, *adaptability* and *flexibility*. These terms are variously referred to in the literature as *ilities* (Filman, 1998; McManus, Richards, Ross, & Hastings, 2007; Ross, 2008), *non-functional requirements* (Glinz, 2007) or *system lifecycle properties* (de Weck, Ross, & Rhodes, 2012; Ross, Beesemyer, & Rhodes, 2012). Here, I will discuss three system lifecycle properties in turn, and relate them to resilience.

Robustness

Engineering has traditionally used prediction and mitigation approaches to deal with uncertainty in systems. Therefore robust systems, which do not change in structure or function despite varying operating conditions, have been well researched. The seminal work on robustness was led by Taguchi (1985) and Clausing (1994) who developed methods to design for robustness, including the quality loss function, off-line quality control and design of experiments. In the literature a robust system is described as insensitive to influences (Ross, Rhodes, & Hastings, 2008; Taguchi, 1993), satisfying a constant set of requirements (Chalupnik et al., 2013; Saleh et al., 2009) and be able to withstand perturbations (Carlson & Doyle, 2000; Jen, 2003). A robust system may degrade but will remain within performance thresholds (Gribble, 2001; Jen, 2003). Robustness can be designed into systems based on expected influences over the design life. However, particularly for complex socio-technical systems, it is impossible to predict all future influences. Optimised systems are designed to be robust to specific, expected influences but they can be fragile to unexpected influences (Carlson & Doyle, 2000) so there is a trade-off between robustness and rigidity. System robustness is therefore not sufficient to achieve system resilience, it must be combined with other system lifecycle properties such as flexibility and adaptability so the system can change in response to influences (Carpenter et al., 2001; Simmie & Martin, 2010).

Flexibility

A flexible system is able *to be changed* in both function and structure in response to influences (Fricke & Schulz, 2005; Haberfellner & de Weck, 2005; Hastings & McManus, 2004; Ross, 2008). For a flexible system to change an external change agent is required, which may be human or otherwise (Fricke & Schulz, 2005; Ross, 2008). There are many other definitions of flexibility used in contexts including economics, organisations and manufacturing (Saleh et al., 2009). These definitions all refer to a system that is able to change or be changed in some way, but in some cases this change is between a set of functions the system already possesses. For example, *machine flexibility* where multiple possible functions are designed into the system from the outset (Sethi & Sethi, 1990). In this research, flexibility is defined as the ability to be changed in new, previously unanticipated, ways.

Adaptability

Adaptability is described in the ecology and social-ecology literature in the context of how ecological systems can demonstrate resilience (Davoudi et al., 2012; Folke et al., 2010). Here, adaptability is defined as the capacity for human agents to influence resilience (Walker, Holling, Carpenter, & Kinzig, 2004). However, as a system lifecycle property, adaptability is defined more generally as the ability of a system to *change itself* using an internal change agent (Fricke & Schulz, 2005; Ross, 2008). In certain domains, including building design (Schmidt, Austin, & Brown, 2009) and electronics (Walker, Trefzer, Bale, & Tyrrell, 2013), the term adaptable is not clearly defined but used to describe a system that changes in some way. (In these fields, the term flexibility is not used interchangeably with adaptability because flexibility is associated with material properties and structural behaviour.) However, there is a consensus in the literature that adaptability, as well as flexibility, involves functional as well as structural changes.

2.1.3 Relating system lifecycle properties to resilience

Robustness, flexibility and adaptability are all aspects of resilience. Table 2-2 shows how these three concepts can be differentiated between, using factors identified in the literature. A system change is here defined as a response to an influence rather than damage to a system's structure or degradation of its function. Also, system changes do not include responses that are pre-designed into a system to accommodate expected influences.

Table 2-2: Summary of distinctions between system lifecycle property terms.

		ROBUSTNESS	FLEXIBILITY	ADAPTABILITY
SYSTEM CHANGE	None	■		
	Structural		■	■
	Functional		■	■
CHANGE AGENT	None	■		
	External		■	
	Internal			■

Table 2-2 shows that there are two conceptual cases not covered by these lifecycle property definitions:

1. A system that changes in function but not in structure
2. A system that changes in structure but not in function

Case 1 can occur in a flexible or adaptable system, if for example some components that were not being used fully are put into operation, realising latent functions in the system. Case 2 can be described as a resilient system. In this case the top-level system function does not change but this is only possible because there are structural changes at a lower system level, i.e. the subsystems are flexible and adaptable (change in function).

By distinguishing between flexibility and adaptability, we can begin to see some of the subtleties in domain-specific definitions of resilience. For example, ecological systems are considered inherently complex and emergent, even at a component level (living organisms are complex). This means that the system has the capacity to change without an external agent, i.e. to adapt. Change within an ecological system is expected, and even welcomed. Conversely, in engineering systems, variability and uncertainty is, as far as possible, designed out. The boundary of an engineering system is usually defined separately to any human agents that might be involved in its operation or maintenance. Therefore, in engineering definitions of resilience, the type of change described is flexibility.

Resilience terminology is used to indicate a system changing in order to continue delivering its main functions as opposed to a robust system where no change takes place. However, it is often not clear what type of change is taking place and at which level in the system (e.g. a sub-system might adapt to maintain functionality at a system level). Changes in a socio-technical system might be assumed or neglected because such systems are often in a constant state of flux. For example, a resilient system might be described as able to adjust to internal and external events over a significant time period (Sundström & Hollnagel, 2006), without specifying if this is a 'designed in' adjustment to a known and anticipated influence (which equates to robustness, as defined above) or if the system is changing in new ways to accommodate unexpected influences (which equates to resilience, as defined above).

The ambiguity of the term resilience could be partly responsible for its prevalence in contemporary systems discourse. Resilience encompasses a range of lifecycle properties that systems have to exhibit in order to survive in adverse circumstances. However, this semantic overloading brings challenges to communicating about resilience, especially with diverse stakeholders.

2.1.4 Relating system attributes to resilience

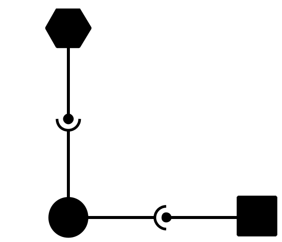
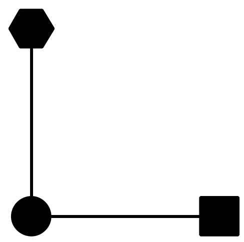
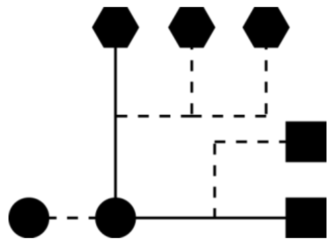
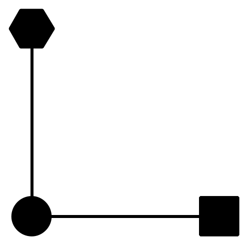
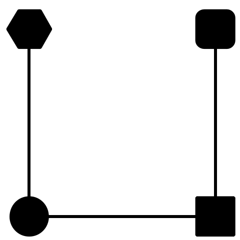
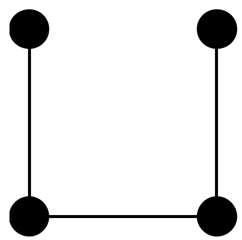
There is another way to look at resilience in addition to looking at characteristics (Table 2-1) and system lifecycle properties (Table 2-2). That is to identify attributes that lead to resilience. These attributes can be built into systems in order to realise certain system lifecycle properties. Table 2-3 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 2-3. For example, 'clustering' is described as the extent to which strongly connected components are grouped into distinct sub-systems, can help to avoid the negative consequences of connectivity by containing the effects of influences to a single cluster (Ash

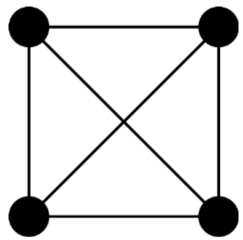
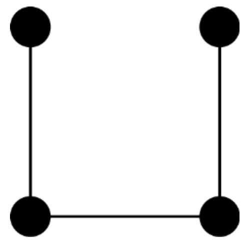
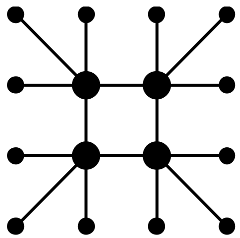
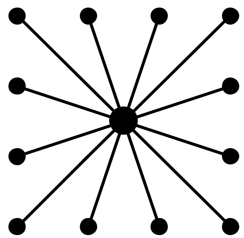
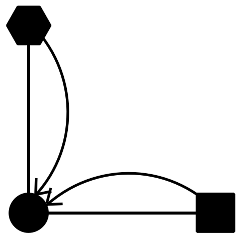
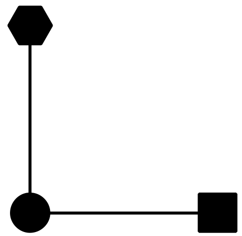
& Newth, 2007). This is a type of modularity. Similarly, 'degeneracy' is a form of functional redundancy where functions in a system can be redistributed amongst different system components (Whitacre & Bender, 2010).

The amount that each attribute increases (or decreases) resilience is dependent on the system, the level within a system the attribute features, 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.'

Table 2-3: Attributes that contribute towards resilience in socio-technical systems. The diagrams show how a system might differ if it had more or less of 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 & Newth, 2007; Baek, Meroni, & Manzini, 2015; Carpenter et al., 2012; Chen & 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 & Jackson, 2009; Whitacre & 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, Ludlow, & Heydari, 2016; Whitacre & 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 & 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)

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 system lifecycle properties that 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 system lifecycle properties.

2.2 Using diagrams to communicate system lifecycle properties

Because of the intricacy and ambiguity of resilience-related terminology, diagrams are often used in the literature to communicate the essential concepts of system lifecycle properties and to distinguish them from each other. For example, I used diagrams in Table 2-3, to consolidate and compare system attributes. Using such diagrams offers the potential for system stakeholders to be more explicit about which characteristics of resilience they are talking about and to avoid domain-specific language that might be unknown or misunderstood.

2.2.1 Purpose and motivations behind system lifecycle property diagrams

The existing literature primarily uses diagrams of system lifecycle properties to support linguistic descriptions of those properties. The ambiguity in the use and definition of terms is reflected in the diagrams that support them, which have few visual commonalities and lack conceptual consistency. This section of the literature review establishes why lifecycle property diagrams are useful and whether the current diagrammatic schemes are suitable for discussions with stakeholders of systems.

Comparing system lifecycle properties

One use of diagrams is to compare two or more lifecycle properties. For example, changeability can be categorised in a block diagram (Figure 2-1) but linguistic descriptions quickly become complex, limiting the number of factors that can be described. A good example of a visual comparison is McManus' 3D *Ility Space* (Figure 2-2). In this framework, lifecycle properties are characterised by the transition of a system between states. By showing robustness, flexibility and adaptability on the same axes, the author differentiates between them by the system's response to changes in three parameters: environment, needs and physical form.

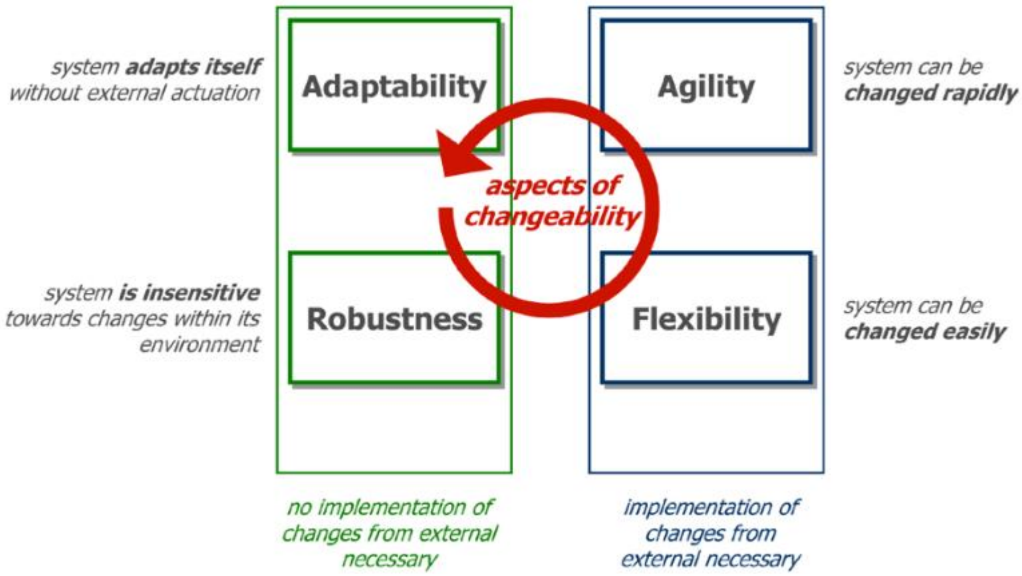


Figure 2-1: Aspects of changeability shown with four lifecycle properties (Fricke & Schulz, 2005).

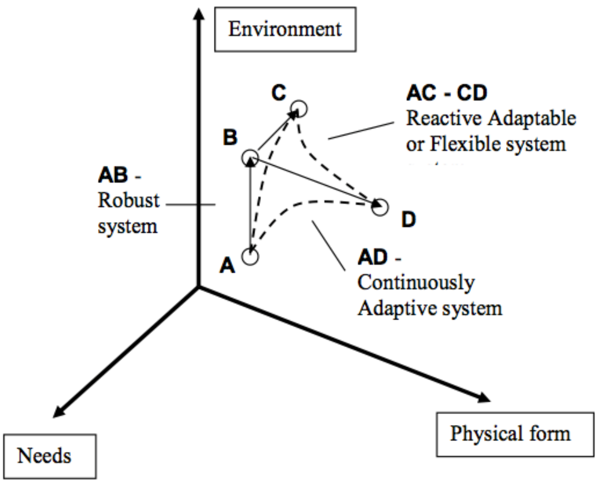


Figure 2-2: Lifecycle property space showing robustness, adaptability and flexibility according to a systems response against three axes of system change (McManus, 2008).

There are not many examples of diagrammatic frameworks being used consistently to compare a broad range of lifecycle properties. An exception to this is the probability-based diagrams by Chalupnik et al. (2013) that are modified to represent robustness, adaptability, versatility, resilience and flexibility. Unlike in Figure 2-2, the diagrams in this set require additional linguistic qualifiers to show the type of change; for example in Figure 2-3 the difference between robustness and adaptability is shown by an explanation on the right hand side.

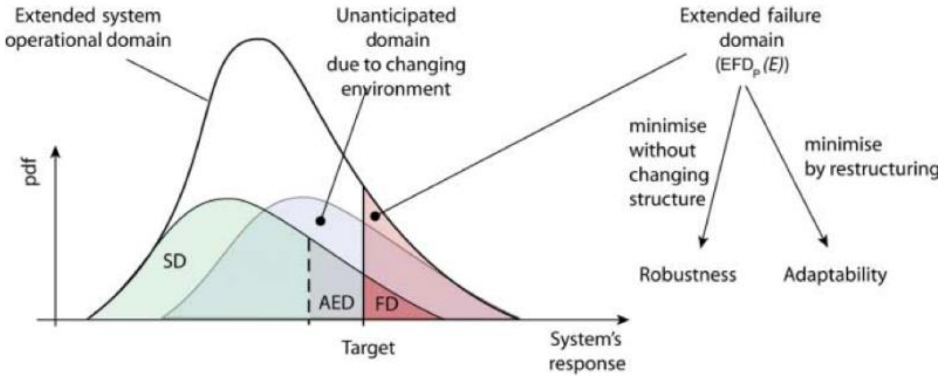


Figure 2-3: Comparison between robustness and adaptability based on a probability density function (Chalupnik, Wynn, & Clarkson, 2013).

One of the clear advantages of using diagrams is the ability to succinctly compare multiple lifecycle properties. But diagrams often require domain-specific skills (visual-spatial in Figure 2-2) or knowledge (of probability density functions in Figure 2-3). Removing the need to label lifecycle properties on diagrams could reduce semantic confusion and fixation on specific terms when discussing concepts in interdisciplinary settings.

Framing author perspectives

Some authors use diagrams to show their departure from commonly used definitions of system lifecycle properties. Urken, Nimz and Schuck use a Venn diagram (Figure 2-4) to show the hierarchy of properties classed as *evolvability* and argue that resilience should be considered as the integration of robustness and sustainability, rather than just being a synonym of robustness (Urken, Nimz, & Schuck, 2012).

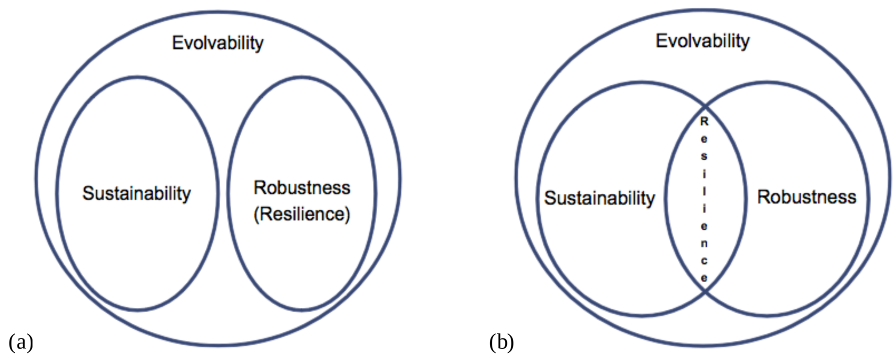


Figure 2-4: Comparison of (a) the conventional view of resilience as a synonym of robustness with (b) resilience as an 'integrative mechanism' (Urken et al., 2012).

Ross, in his early work (Ross, 2006), uses an alternative approach to distinguish robustness from *rigidity* (Figure 2-5). In engineering the traditional view of robustness stems from Taguchi's seminal work: 'Robustness implies that the product's functional characteristic is not sensitive to variations in the noise factors.’ (Taguchi, 1985) However the term has additional interpretations in other domains and colloquial use. Rigidity is a term that also originated in engineering but is not related to changeability. The rigid system undergoes no change compared to the robust system, which maintains the same value delivery in spite of an external context change. This suggests that there may be some internal structural or functional change within the ‘black box’ of a robust system (i.e. flexible or adaptable sub-systems).

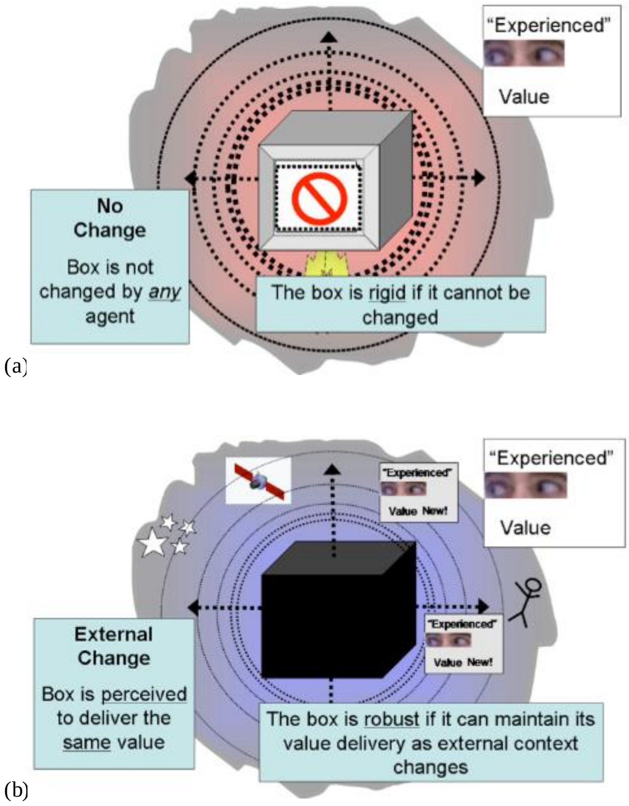


Figure 2-5: Illustration of the difference between (a) rigidity and (b) robustness (Ross, 2006).

Providing a graphic comparison between terms that are similar is useful for communication. The nuances between system changes, which may or may not affect the system deliverables, are best described with a representation of the system itself (as in Figure 2-5) rather than the conceptual relations between terms (Figure 2-4). A systems view also reduces the need for semantic qualifiers to be used with diagrams, as discussed for Figure 2-3.

Understanding changeability

Changeability is a challenging concept to represent. In the ecological resilience literature, the idea of a system changing over time is described using the adaptive cycle model (Figure 2-6). These continuous cycles of change happen at different levels within a system, with change at one level influencing change at another level.

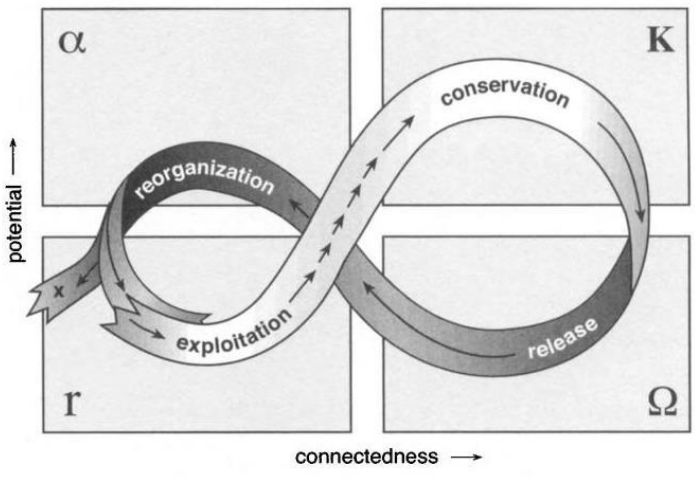


Figure 2-6: Stages of the adaptive cycle where, 'r' is rapid growth to overcome competition, 'K' is slow growth to exploit opportunities, 'Ω' is system breakdown resulting from fragility and over connectedness, and 'α' is reorganisation and emergence of new opportunities (Gunderson & Holling, 2001).

Ultimately, the aim of understanding lifecycle properties is to establish how industry practitioners can design for changeability. Some linguistic treatments of system lifecycle properties use a holistic approach, relating system lifecycle properties to architectural attributes such as modularity. Examples of this include a means-ends network in Figure 2-7 and an uncertainty classification in Figure 2-8. On some accounts, there is no formal distinction between lifecycle properties and architectural attributes but generally, the latter can be designed into a system so as to give the required lifecycle properties. The means-end hierarchy in Figure 2-7 shows this, progressing from 'designed-in' architectural attributes (towards the bottom) to lifecycle properties (towards the top). Hastings and McManus (2004) also relate the lifecycle properties to different types of uncertainties and risks (Figure 2-8). These linguistic treatments tend to include a wide variety of terms. It is unclear whether this is due to overlaps in the definitions or because multiple terms are used depending on the type of system. An approach driven by graphic representations of a system would help to eliminate unnecessary terms and ensure all permutations of changeable system behaviour are accounted for.

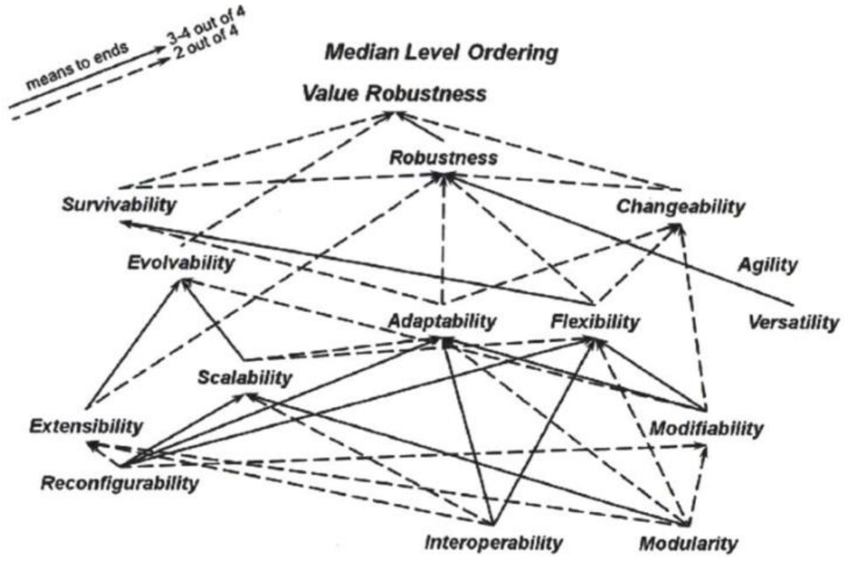


Figure 2-7: Means-ends lifecycle property hierarchy (de Weck, Ross, & Rhodes, 2012).

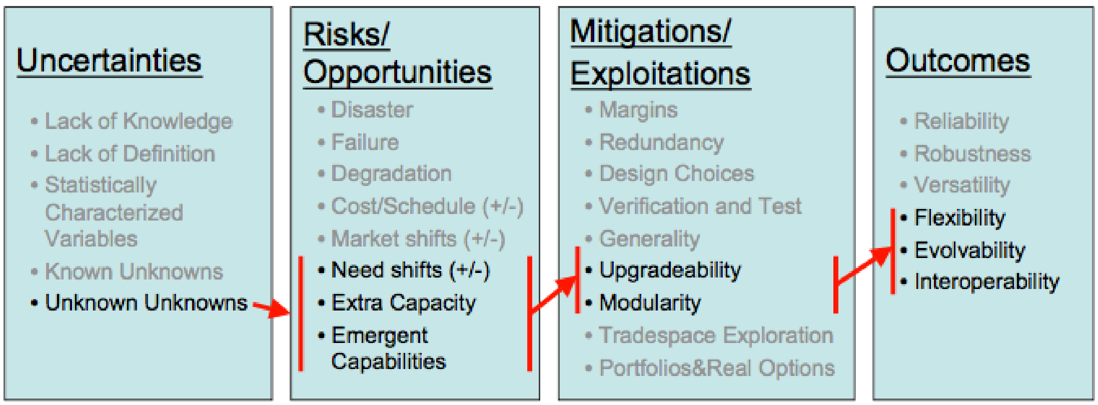


Figure 2-8: Framework of uncertainties and effects (Hastings & McManus, 2004).

Defining system abstraction

Notably in the lifecycle property literature, diagrams are rarely used to define the level of system abstraction or frame of reference. The changes that 'design for changeability' addresses are those that occur when the system is in operation. Systems are defined by perspective, and therefore the notions of change and operation are perspective-dependent too. For example the principles of design for changeability would not typically be applied to a product system in the manufacturing stage but could be applied independently to the manufacturing process as a system in its own right (ElMaraghy, 2005; Mehrabi, Ulsoy, & Koren, 2000). Most discussions of lifecycle properties focus on product development or a specific industry but this research is deliberately general so that it applies to different system types, including products and processes, at different levels of abstraction.

Despite the lack of graphical representations, the importance of defining a system boundary is frequently discussed the literature (de Weck, Eckert, & Clarkson, 2007; Haberfellner & de Weck, 2005; McManus, Richards, Ross, & Hastings, 2007). Ross' black box metaphor (Figure 2-5) shows how a boundary might be incorporated in a general framework (Ross, 2006). This framework is particularly effective in showing the origins of system influences and the change agents that respond to influences.

An example from the manufacturing domain is shown in Figure 2-9 where lifecycle properties are mapped against the product and production architecture. The transition from 'built-in' system architectural attributes to lifecycle properties at a higher level of abstraction shows that lifecycle properties can propagate through different levels from sub-systems to super-systems (Crilly, 2013). Although this representation is domain-specific, it highlights the value of considering a stakeholder's frame of reference. Defining a system boundary diagrammatically allows both the process of change and levels of the system to be made explicit.

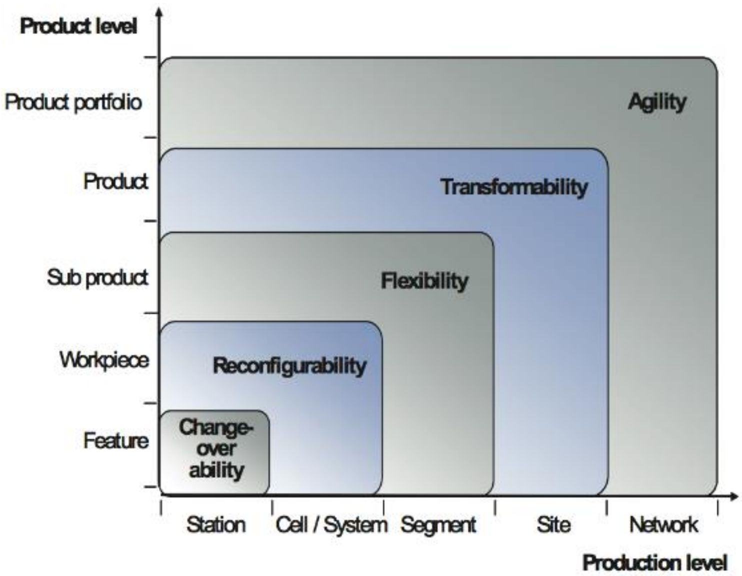


Figure 2-9: Types of changeability in a factory (Wiendahl et al., 2007).

2.2.2 Features that characterise system lifecycle properties in diagrams

Diagrammatic representations are useful in understanding resilience. They can be used to compare concepts, frame an author's perspective and support understanding of complicated concepts. In order to use diagrams to communicate with system stakeholders about resilience, we must establish which system features need to be represented.

System stimulus

One of the conceptual difficulties with changeability is that a clear distinction is not always made between the *stimulus* affecting the system and the system's *response*. These two aspects of changeability are not often shown on the same diagram but the difference is alluded to by lifecycle property diagrams that show time progression (Figure 2-10) or use state/epoch transitions (Figure 2-11).

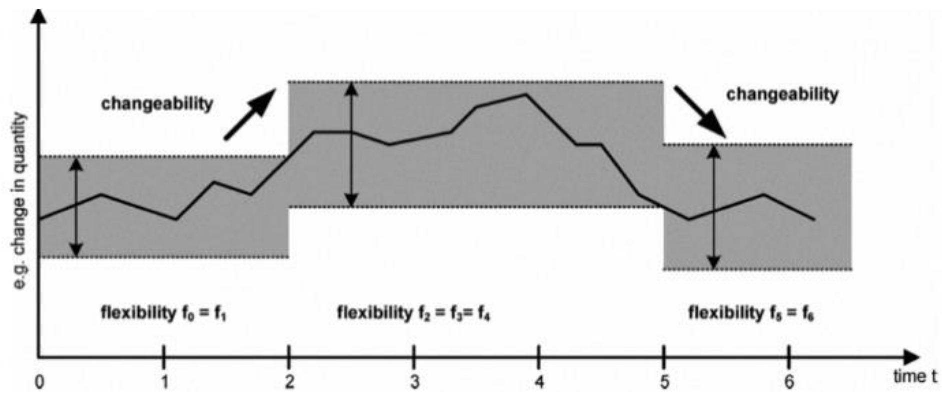


Figure 2-10: System responding to changes in demand over time within threshold values (defined as flexibility) and shifting to meet new market needs with new thresholds (defined as changeability) (Nachtwey, Riedel, & Mueller, 2009).

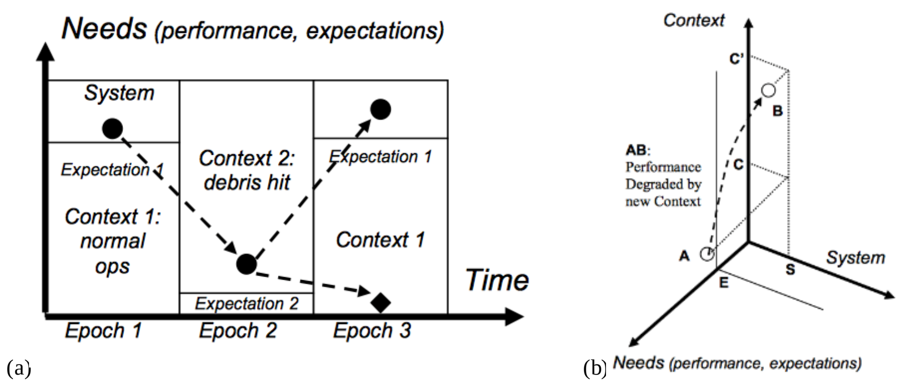


Figure 2-11: (a) Epoch model of survivability and (b) 3D ility space (McManus et al., 2007).

Various authors refer to stimuli as *disturbances* (Carlson & Doyle, 2000; Urken et al., 2012) or *perturbations* (Beesemyer, 2013; Chalupnik et al., 2013; Jen, 2003). These terms have negative connotations and are not visualised effectively in the existing diagrams. Also, perturbation by definition can refer to the cause of a change, the change itself or the act of changing. Here I use *influences* to refer to system stimuli.

Some diagrams, such as Figure 2-11a, show the system within a changing *context* but this only accounts for exogenous influences, typically including natural events or market behaviour (where nature and the market are taken to be outside the system). There are also endogenous influences that can result from user behaviour or technical changes (where these users and changes are taken to be inside the system). Figure 2-11b is unique in showing both exogenous and endogenous influences with the 'context' and 'system' axes respectively. It is important that both types of stimuli are shown because lifecycle properties are characterised by the source of the influence as well as the system response. The term *needs* in Figure 2-11 could cause confusion since changing stakeholder needs can also be a system stimulus (see caption in Figure 2-10).

System response

Separate from the system stimulus is the change that the system may or may not undergo: a response. Whether the system responds to a stimulus by changing is typically what distinguishes *robustness* (no change) from *adaptability* and *flexibility* (change).

Like system stimuli, responses can be either endogenous or exogenous, which by consensus in the literature is the distinction between adaptability (endogenous) and flexibility (exogenous). This basic categorisation is shown in Figure 2-1; agility and flexibility in the right hand column require external implementation of change whereas adaptability and robustness do not (Fricke & Schulz, 2005). Agility is used less frequently in the literature to describe the speed of change (Haberfellner & de Weck, 2005).

The clearest illustration of the response source was developed by Ross (2006). In Figure 2-12, a change agent is shown by a stick man located inside the system for the adaptable system and by an arm reaching from outside the system for the flexible system. Although the change agents in this diagram are seemingly human, they could more generally represent any agent that can respond to a stimulus and change the system.

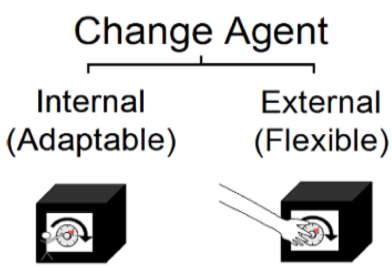


Figure 2-12: Representation of the system response origin (Ross et al., 2008).

Value delivery

Related to but distinct from system changes is the value delivery of the system. Some authors refer to *value robustness*, defined as 'the ability to maintain value delivery in spite of changes in needs or context' (Ross & Rhodes, 2008). This encapsulates the reason why there has been increasing interest in systems that can change to accommodate uncertainties while in use rather than just surviving. In modern complex systems, changing needs and context are almost inevitable and, as stated by Ross et al., 'The goal of system design is not robust systems per se, but rather the delivery of value to system stakeholders.' (Ross et al., 2008).

Stakeholders will have certain expectations of the system and it will have to perform within these thresholds in operation to avoid system failure. The diagrams in Figure 2-10 and Figure 2-11, provide a clear but simplistic visualisation of these thresholds. Some systems do not change when subjected to stimuli but continue to deliver the required value. Other systems deliver the required value by undergoing functional or structural changes. The former case is consistent with literature definitions of *robustness* and the latter with definitions of *adaptability* and *flexibility*. Diagrams that show the architecture and hierarchies of the system, such as Figure 2-5, can be developed to show these system changes, and thus more clearly show the conceptual distinction between types of value delivery.

A change in the system's operating conditions or the context of operation may result in a new definition of value. This is a consistent with the ecological definition of resilience, which allows for the existence of multiple stable states as long as the primary functions are retained (Walker et al., 2004). The process of changing to a new system state is sometimes described as *transformability*, which is defined as 'the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable' (Walker et al., 2004) or 'the capacity to cross thresholds into new development trajectories' (Folke et al., 2010). Another lifecycle property, *versatility* is sometimes used in a similar way. In this case, the system's value delivery remains constant but is useful in different operating contexts, which can be seen as a type of robustness.

2.3 Literature review summary

In order to understand resilience in socio-technical systems, this literature has looked at how the concept of resilience is defined and applied across domains. Resilience, as a standalone concept, is primarily discussed in the ecology and sociology literature. Here resilience is applied to complex, evolving systems, with a focus on observing and explaining how these systems survive and thrive. However, what this work does not address is how to understand resilience in the context of design practice and socio-technical systems. This means that it is not clear how to go about communicating with system stakeholders about resilience. Especially stakeholders who may not have thought about these concepts before, such as those working on a technical sub-system within a socio-technical system.

Therefore, to develop an understanding of how to break down and structure the concept of resilience, this literature review has looked to the field of systems engineering, where resilience is treated as one of a group of system lifecycle properties and the aim is to be able to design such properties into technical systems. Here system lifecycle properties are applied to technical systems that are designed, measured, and controlled by human agents. These properties are realised in systems through certain attributes including modularity, redundancy and decentralisation. The relationship between system lifecycle properties and the function and structure of systems is complex. Therefore, system lifecycle property diagrams were evaluated to identify: what people need to communicate with system lifecycle property diagrams; and the features that characterise system lifecycle properties.

There are many different ways that system lifecycle properties can be represented graphically. The examples presented in this review have been developed by their authors to serve particular purposes but none were explicitly intended for communication with system stakeholders across different domains. More generally, there are no studies in the literature that look at communication about resilience between stakeholders working within socio-technical systems. The literature demonstrates that there are several barriers that make it difficult for stakeholders to think about resilience in the context of their own work. These include: confusion over what resilience is, and the complexity of socio-technical systems. The approach commonly taken in the literature, of conducting retrospective case studies of resilience in systems, will not answer these questions about how and what to communicate.

This literature review has demonstrated the important of the concept of resilience across academic domains. Some authors study resilience through retrospective case studies of complex systems, others break down the concept and relate it to technical system attributes. However, few authors look at resilience in the context of socio-technical systems, which are partly designed and partly evolved. Fewer still talk to stakeholders of systems as a gateway for understanding resilience. This literature review is a foundation for a socio-technical stakeholder led approach, which requires communication across domains and the structuring of resilience in the context of complex systems, which in this case is achieved using diagrammatic frameworks.

3 Research design

From the literature it is clear that resilience is an important concept in domains that work within and contribute towards socio-technical systems. Work is being done in individual domains both about specific types of system resilience (e.g. communities facing natural disasters) and about the definitions of system lifecycle properties (e.g. the difference between flexibility and adaptability in systems engineering). However, there is a lack of research focusing on multi-disciplinary stakeholders who are already working on and within socio-technical systems.

The end goal of this research is to contribute towards an understanding of how to design resilient systems. If we use a loose definition of a resilient system, as one that survives in uncertainty and change, then this goal is clearly shared with stakeholders of many socio-technical systems. This thesis therefore takes a stakeholder led approach to answer the research question that was proposed in the introduction:

What can we understand about resilience from talking to system stakeholders?

This question has been addressed using an approach outlined in this chapter. Here, the research methods and overall approach will be discussed. Methodological details about individual studies are given alongside the analyses in Chapters 4-6.

3.1 Research methodology

The epistemological stance taken in this research is postpositivist (Lincoln, Lynham, & Guba, 2011). Therefore, there is an assumption that the reality presented here was influenced by my own background and that of the stakeholders I have spoken to. The concept of resilience is not well understood in the literature or in design practice. This is further complicated by looking at design practice in the context of socio-technical systems, which are emergent and irreducible. To explore these complexities in enough depth, a qualitative approach was required. A flexible research design was used, with an evolving design, a focus on participants' views, and an appreciation of the 'researcher-as-instrument' (Robson, 2011). More generally, this research sits within the field of design research.

There is still a strong emphasis in resilience research on conceptual work, building theories from the literature. Although there are a significant number of empirical studies on resilience, they are mostly about social or ecological systems (Bhamra, Dani, & Burnard, 2011), and they typically focus on past events. By contrast, the emphasis in this research is on how resilience can be understood in the context of stakeholder's daily practice, which involves looking across system timescales (from the past to the future) and searching for a practical application of resilience concepts. This means that the methodological approach I have used is unique within resilience research; it has evolved with the needs of the research rather than centred on work already done in the field.

The methodology in this thesis was influenced by two fields of study: systems engineering and systemic design. Both of these interdisciplinary fields deal with solving complex system design problems, with an appreciation of both people and technology. However, broadly speaking, systems engineering is technology-centred (de Weck et al., 2011), whereas systemic design is human-centred (Jones, 2014; Ryan, 2014). Systems engineering, was the dominant guiding force in the first study (Chapter 4), with the emphasis changing to systemic design in the later studies (Chapters 5 and 6).

At the start of this research, I intended to answer the main research question by understanding how to design changeability, an important aspect of resilience, into technical systems, namely products. Therefore, the literature review (Chapter 2) initially focused on work done in the field of systems engineering, and Study 1 (Chapter 4) aimed to explore stakeholder understanding of product changeability. However, the themes that emerged from Study 1 were as much about social systems as they were about technical systems. Many of the participants in this exploratory study attributed changeability to people's actions and interactions, rather than to technology. To compound this, it became apparent that the concept of resilience is intrinsically linked to the perspectives of individual stakeholders. Therefore, the literature review was expanded to include more domains, and the data from Study 1 was reanalysed to include themes related to socio-technical changeability. Systemic design, which combines design thinking and systems thinking, provides a more complete treatment of social system complexity within the context of system design when compared to systems engineering. This follows the belief that all technical (and natural) systems are entangled with social systems (Ryan, 2014). The influence of systemic design can be seen in the latter parts of this thesis, particularly in Study 3, where there is an emphasis on stakeholder representations of systems. As such, the methodological approach in this thesis attempts to balance the importance of both social and technical systems, but takes a stakeholder led approach to understanding both.

The strength and uniqueness of this research can be attributed to its multidisciplinary outlook, learning from work across resilience and systems domains to deal with the complexity of this topic. One common theme across these domains is an emphasis on visual representations to communicate and understand concepts. Three visual thinking activities are used in this thesis: graphic ideation, graphic communication, and graphic elicitation (Crilly, Blackwell, & Clarkson, 2006). Graphic ideation was used in Study 2 (Chapter 5) to develop a framework to represent resilience, supported by previous work including a review of diagrams in the literature (Chapter 2). Graphic communication was also used in Study 2 to communicate resilience concepts to workshop participants as well as in presenting illustrative examples from the workshop. Graphic elicitation was used in Study 3 (Chapter 6) to discuss resilience concepts with interview participants. However, the process was slightly different than the elicitation described by Crilly et al. (2006), since it focused on 'participatory diagramming' (Kesby, 2000) where the participants ask to produce their own diagrams in the interviews (also see Bagnoli, 2009). This meant that the participants were undergoing their own processes of graphic ideation and communication rather than reflecting on diagrams produced by the researcher.

3.2 Research framework

To answer the main research question, this research has been broken down into four sub-questions:

What can we understand about resilience from talking to system stakeholders?

RQ1. What can we understand about resilience from the academic literature?

RQ2. What can we understand about resilience from stakeholders of different technical systems?

RQ3. What can we understand about resilience from stakeholders of different socio-technical systems?

RQ4. What can we understand about resilience from stakeholders in different parts of the same socio-technical system?

The first of these questions (RQ1) was proposed in the introduction (Chapter 1) and answered in the literature review (Chapter 2). These four research questions are presented together here, but in practice they evolved based on the studies in this thesis. Originally, Study 1 was a designed to focus on the concept of changeability in technical systems. This was because the literature suggested that there was a gap in the research around understanding changeability from the perspective of system stakeholders. However, as I analysed the findings from this study I realised that many of the emerging themes were in fact related to the broader concept of resilience and were perceived as socio-technical, rather than technical, issues. Therefore, I reframed the research, evolving the scope in terms of its topic, systems of interest and academic area (as described in the literature review).

	START OF RESEARCH		END OF RESEARCH
TOPIC	Changeability	→	Resilience
SYSTEMS OF INTEREST	Technical systems	→	Socio-technical systems
ACADEMIC AREA	Systems engineering	→	Systemic design

Following this reframing, I reanalysed Study 1 to look at broader questions about the nature of resilience and stakeholder perceptions of change in both social and technical systems. This is why the design of Study 1 does not seem immediately obvious when considering RQ2. The progression of the subsequent studies was more linear, with each research question emerging from the previous studies.

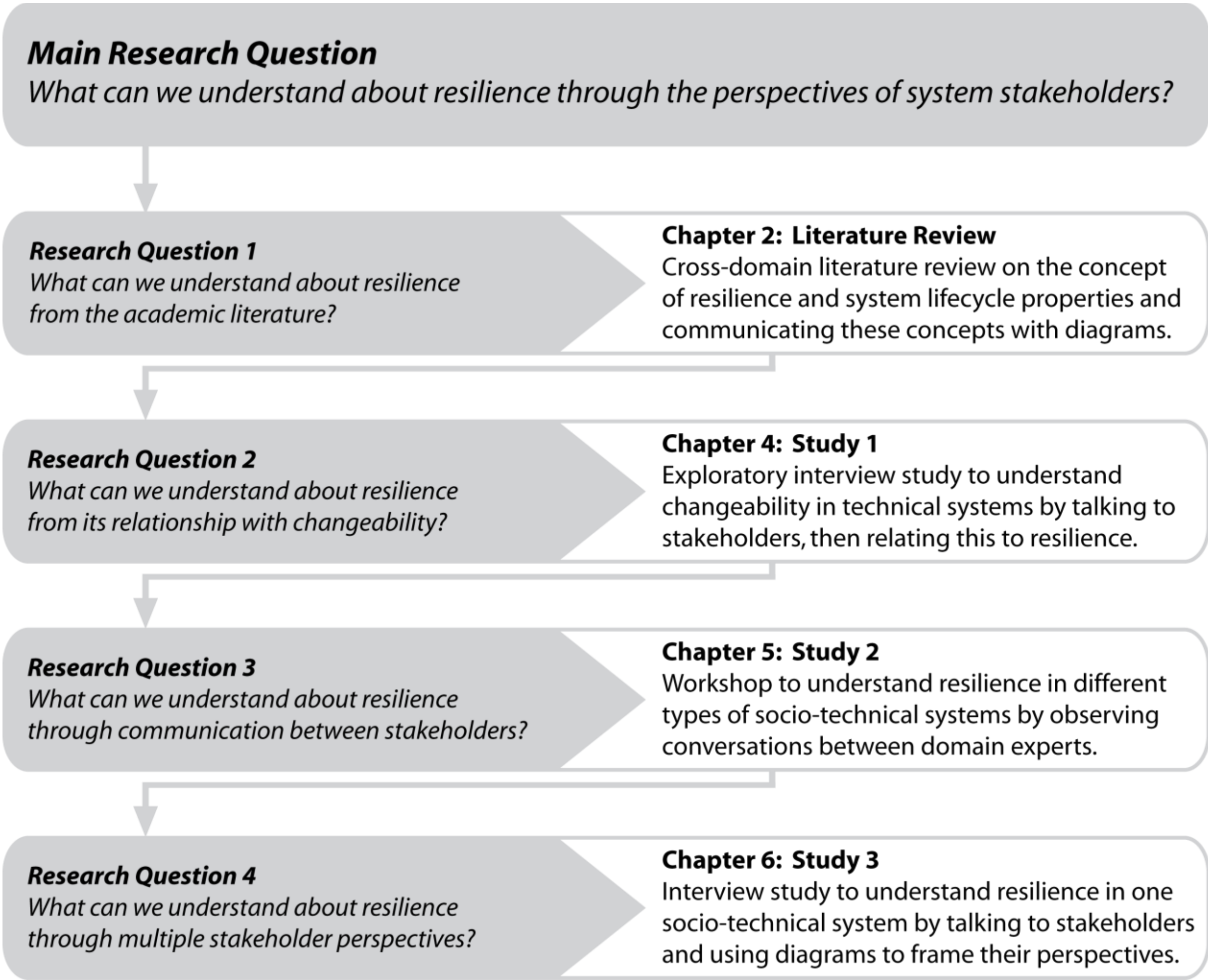


Figure 3-1: Diagram showing the progression of research questions and corresponding studies.

As shown in Table 3-1, this research framework is consistent with two that are widely used in the field of design research: the *spiral of applied research* (Eckert, Stacey, & Clarkson, 2003) and *DRM: Design Research Methodology* (Blessing & Chakrabarti, 2009). Seven of eight types of research proposed in the spiral of applied research are covered in this thesis. There is minimal evaluation of the visualisations and diagramming methods produced in this thesis. This is because they are used as a way to elicit knowledge, rather than proposed as a tool in their own right. The research in this thesis corresponds to a Descriptive Study in the DRM framework (Blessing & Chakrabarti, 2009, p. 18).

Table 3-1: Comparison of research design with two popular design research frameworks: the spiral of applied research and DRM.

<table>
<tr><th>MY RESEARCH</th><th>SPIRAL MODEL</th><th>DRM</th></tr>
<tr><td>Academic literature study (Lit. Review – Chapter 2)</td><td>Academic dissemination</td><td rowspan="9">Descriptive study (Comprehensive)</td></tr>
<tr><td rowspan="2">Exploratory interview study (Study 1 – Chapter 4)</td><td>Empirical studies of design behaviour</td></tr>
<tr><td>Evaluation of empirical studies</td></tr>
<tr><td rowspan="2">Workshop study (Study 2 – Chapter 5)</td><td>Development of theory</td></tr>
<tr><td>Evaluation of theory</td></tr>
<tr><td>Visualisations throughout</td><td>Development of tools and procedures</td></tr>
<tr><td></td><td>Evaluation of tools and procedures</td></tr>
<tr><td rowspan="2">Concept mapping interview study (Study 3 – Chapter 6)</td><td>Introduction of tools and procedures</td></tr>
<tr><td>Evaluation of dissemination</td></tr>
</table>

3.3 Scope

This research was designed to find out what we can learn about resilience from stakeholders of socio-technical systems, including their current level of understanding about resilience and how understanding of resilience could be improved. I have not attempted to definitively answer the question of how to design a resilient system, although it has been assumed that understanding resilience from the perspective of stakeholders is a necessary step towards that goal. In addition, some aspects of resilient system design have been touched upon, for example, through the discussion of system attributes.

3.4 Methods used in this thesis

This research aims to find out more about resilience by talking to system stakeholders. Therefore the main challenge in identifying appropriate methods was, how to communicate effectively about complex concepts with stakeholders. One-to-one encounters offer a chance to explore issues in great depth so were the primary form of data collection. However, collecting data from industry comes with a set of challenges and ethical considerations, which are discussed in more depth here (specific details about each study, e.g. participant samples, are given in Chapters 4 – 6).

3.4.1 Interviews

Studies 1 and 3 in this thesis use qualitative interviews. These interviews were semi-structured, to allow the researcher to guide the conversations whilst also providing the flexibility to respond to the individual experience and knowledge of each participant (Robson, 2011). This approach is particularly pertinent for this research since the emphasis is on the differences as well as the similarities in how participants perceive resilience. Interview guides were produced, with a list of questions, as a rough outline to follow in the interviews for each study (Bryman, 2012: p471).

Interviews allow for rich data collection and exploration of a subject that is not well covered in the academic literature. However, the trade-off is the time-consuming nature of the process, including activities not directly related to the data analysis, such as, recruiting and managing participants (Robson, 2011). Another consideration for using interviews is that the researcher is linked to the data, both in the way they respond to participants and in the way they treat the data. This raises questions like, what would this research look like if someone else had conducted it? For this research, the relationship between the researcher and the interview process is important. There are a lack of existing empirical studies into resilience and the interdisciplinary nature of the research means that it is beneficial for the researcher to approach the interviews with a large body of accumulated knowledge, in order to make new connections. The most problematic feature of using interviews to collect data is the assumption that the participants' descriptions of their systems are reliable (Brewer, 2000), particularly with this type of research where interview samples can be quite diverse. To avoid bias, the samples for each interview study have been considered carefully. To ensure any remaining bias is transparent, each sample is discussed in detail in the corresponding chapters of this thesis.

3.4.2 Workshop

In the second empirical study (Chapter 5), a workshop was used to explore how resilience could be communicated across domains. Methodologically, this workshop is what is discussed as a *focus group* in the qualitative research methods literature. The main difference between this workshop and traditional focus groups is that the discussion in the workshop was open ended, with the scene set at the beginning of the discussion but no scripted questions.

In workshops, group discussions highlight the areas where participants have shared views and where there are contentions (Bryman, 2012). It was therefore a useful method to use mid-way through the study to build on and refine the findings from Study 1. This workshop was used to prioritise areas of research going forward, and also to develop a communication framework to talk about resilience with diverse stakeholders.

3.4.3 Visual methods

In the third empirical study (Chapter 6), a system mapping exercise was used to elicit information from interview participants. Asking participants to draw diagrams in qualitative interviews can be an effective way to collect data, particularly when there are potential barriers to communication. For this reason drawing is most often used in cross-cultural research or with children, although its potential for wider application has been acknowledged (Bagnoli, 2009; Crilly et al., 2006; Umoquit et al., 2008). There are generally two approaches to diagramming in interviews: *participatory diagramming*, where the participant is asked to produce a diagram in the interview, and *graphic elicitation*, where the participant is asked to respond to a pre-prepared diagram (Umoquit et al., 2008). Asking interview participants to draw diagrams, allows them to communicate their explicit and tacit knowledge of systems, which can then be used for deeper reflection and ideation on difficult to understand concepts (Crilly et al., 2006; Kesby, 2000). Therefore, it was thought that using diagrams would be useful in this research, to help stakeholders distinguish between related resilience concepts and to overcome confusion about resilience terminology. It has also been suggested that using diagrams in interviews may reduce participants' reliance on standard answers or practiced narratives (Bagnoli, 2009; Wheeldon & Faubert, 2009). This is particularly useful in this research where the aim is to gain a deeper understanding of resilience by talking to system stakeholders than could be found in system documentation or official statements.

The literature shows that there is a trade-off between highly structured and unstructured diagramming exercises. Using structured diagramming exercises can help to overcome issues associated with poor visual literacy and low confidence in participants (Bagnoli, 2009; Crilly et al., 2006). However, an unstructured approach allows participants to express their own perspective, and reduces the effect of the researcher's interpretation guiding the participant (Bagnoli, 2009;

Prosser & Loxley, 2008). This trade-off must be managed in the design of diagramming interview exercises.

3.5 Other possible methods

There are other research methods that could have been used to investigate the main research question. The two that will be discussed here are ethnography and action research. These methods are consistent with the research objectives, as they could have been applied to answering the overall research question. However, they were not used for practical reasons relating to the timing of this research.

3.5.1 Ethnography

An ethnographic approach would be an appropriate way to study the resilience in the context of a particular organisation (Robson, 2011). In contrast with interviews, a more observational approach would avoid reliance on participants to accurately represent their work. Using ethnography could also be a good way to explore the practical issues in organisations that relate to designing resilience into socio-technical systems.

This research is based on the premise that to understand resilience, we have to look at socio-technical systems across different domains and from multiple perspectives. This means that researching across multiple organisations, and understanding multiple cultures, is more important than researching within a single organisation. Ethnography's focus on contextual factors means that it would not be an efficient way to collect data. It would be difficult to gather enough diversity in perspectives using ethnography in a three year time frame, particularly considering the amount of conceptual work that was required to get to the point at which empirical research in this thesis could be conducted (for more discussion of this type of study see Section 7.5 on future work).

3.5.2 Action research

The main research question of this thesis refers to being able to design resilient systems. To achieve this aim, action research would be an ideal method to use (Bryman, 2012; Robson, 2011). The aim of an action research approach could be to improve the understanding of stakeholders about resilience. An intervention could be designed with visual methods based on the diagrams and concept maps in this thesis. It would be possible to determine if understanding of resilience had improved amongst a stakeholders, but much harder to determine if an increased understanding led to increased system resilience. This is due to a wider issue in resilience research; it is difficult to measure a change or to compare different changes in a large complex system.

The other reason why action research was not used in this thesis is that the theory on resilience in socio-technical systems is underdeveloped. This research necessarily focused on understanding resilience based on what stakeholders already know.

3.6 Data collection

The interviews and workshop were audio recorded and transcribed. Written notes were also taken as the participants were talking. I transcribed most of the interviews conducted in this research. This was to increase familiarity with the data (Bryman, 2012: p486). However, the workshop audio was transcribed by a Policy Intern at CSaP (Centre of Science and Policy) who was a collaborator on the workshop. Also, five of the interviews in Study 3 were outsourced to a professional service.

For the exploratory study, 7 out of 14 interviews were conducted with Skype video conferencing or over the phone, with all others conducted in person. Although it was difficult to use physical prompts with video conferencing and phone calls, the interviews still lasted the same length of time and the data collected was comparable in coded content to the other interviews.

In the final study, where a system mapping exercise was used in the interviews, these maps were retained. To link what the participants said with what they drew on their map, the concept maps were recreated digitally with slide sequences (in PowerPoint) to show how the picture was built up, with transcribed text linked to each participant action (see Chapter 6 for more details).

3.7 Data analysis

In all cases, the data, in the form of transcripts, was coded iteratively using Atlas.ti analysis software. The resulting codes were grouped into key themes and relationships. As with all qualitative research, for the analysis to be useful the researcher must make subjective decisions about the importance of themes (Thomas, 2006), but validation methods were used to ensure the analyses were trustworthy (see Section 7.4).

For the initial exploratory interview study, Study 1, I used a general inductive approach to data analysis. The general inductive approach is similar to grounded theory (Corbin & Strauss, 2008).

The analysis was essentially inductive, with findings emerging from the raw data (Thomas, 2006). These findings were grouped into themes related to the research question. There were no preconceived ideas about what these themes might be. However, grounded theory requires the researcher to avoid predetermined ideas from the literature, whereas this research required the researcher to make connections between the interview data and existing theories on the concept of resilience.

In Study 2, the workshop data was coded using existing themes from the literature and the first study as a rough guide. By this point, I had developed the conceptualisation sufficiently to be able to narrow the focus down to 'resilience' rather than general themes relating to system lifecycle properties. Once this study was completed, it was clearer which themes were most important from the first study, so the exploratory interviews were recoded to increase the depth of analysis.

For the third study, the interviews were also analysed using a general inductive approach. However, here a pre-existing code list was used, based on previous findings. This list was subjected to additions and amendments as required. The system maps produced by the participants were analysed alongside the interview transcripts.

3.8 Ethics

There were no prohibitive ethical issues related to this research since there was no physical participant contact, administered treatment or deception involved. However, the ethical implications of interacting with stakeholders in interviews and workshops have been considered, including confidentiality, fair treatment and reputational risk. For the interviews, an ethical statement was produced detailing the interview procedure, which was reviewed by the Ethics Representative for the Engineering Design Centre along with an information sheet and consent form for interview participants.

3.8.1 Consent

All of the interview participants were fully informed about the purpose and the procedure of the study and their consent was obtained with a form prior to the interview. No reward or incentive was given to the participants and no judgement was made of individual performance although the participants were selected for their expertise.

In the case of the workshop study (Chapter 5), the participants were fully informed of the nature of the workshop, although no consent forms were signed.

3.8.2 Recording data

Digital data was kept on encrypted memory sticks and any paper copies were kept in a locked drawer. A file identifying the interviewees and linking them to the transcripts and audio files was also kept securely to ensure traceability of the data if needed. Interviewees were free to deny recording permission, request copies of any recorded data or ask for it to be destroyed at any point. Data that was not relevant or useful to the study has not been collected.

All data presented in this thesis has been anonymised with the reputation and identity of participants, organisations and institutions protected. Direct quotations are used throughout this thesis to support the discussion. In some cases, these quotations are edited to ensure the speaker is unidentifiable. Care has been taken to avoid any quotations that may be inflammatory, especially since these types of remarks were not relevant to the research objectives.

3.9 Validation

Validation of qualitative interview data is a subject of contention because this type of data analysis contravenes the conventional criteria applied to experimental or quantitative studies: internal validity, external validity, reliability and objectivity. Lincoln and Guba (1985) outlined four alternative measures of 'trustworthiness': credibility, transferability, dependability and confirmability. In the discussion, these measures are used as a framework to ensure this research is valid (Section 7.4).

3.10 Research design summary

The theoretical stance in this research was largely driven by the complexity of the concept of resilience. It became apparent early on in the research that to understand resilience, we must study it in the context of complex socio-technical systems. To deal with this complexity, a qualitative approach was taken, inspired by the fields of systems engineering and systemic design. The main research question was broken down in stages, with a new research question proposed after each study, then appropriate methods chosen to address each question. The research design is unique within the field of resilience because of the aim to understand what resilience means for stakeholders across domains and at multiple levels of abstraction.

4 Understanding resilience through its relationship with changeability

The literature suggests that changeability, or the ability of a system to adapt and be flexible, is related to resilience. However, changeability is not well understood as a concept. This is particularly true in the context of technical systems. Many technical systems survive over long periods of time in the face of unexpected influences but it is not clear what allows them to do this and if it is the result of design choices. Therefore, this Study explores the role of changeability in technical systems and how that contributes (or not) towards the resilience of those systems, in order to answer RQ2:

What can we understand about resilience from its relationship with changeability?

To answer this question I chose to focus on technical systems. This approach is consistent with the literature on changeability, where system lifecycle properties in technical systems are related to architectural attributes. I thought these architectural attributes would be more readily identifiable in technical systems than in social systems. The participants in the exploratory study worked in diverse domains, but they were all stakeholders of organisations producing or using technical systems, and had a deep understanding of their technology. These organisations also necessarily think about social systems (e.g. employees, users, or external teams of people running processes). The aim of the exploratory study was to discuss changeability in the context of products, which could include hardware, software, or services produced by an organisation for a group of users. I thought that, because user needs and the context of use for these products would change over time, the product itself must change, and therefore, discussing products would show the current state of stakeholder knowledge about changeability concepts.

4.1 Method

All of the interviews took place between March 2014 and January 2015. Each one lasted between 44 and 82 minutes in length. The first six interviews were conducted in person at the participants' place of work, with all participants based in Cambridge except E04, who was based in London. The remaining participants were spread around the UK and further afield (E12 was based in Germany, and E14 was based in the US), so these interviews were performed over video call with the exception of E13, who was interviewed in person. Before the interviews, the participants were told the purpose of the study.

The interviews were semi-structured (Breakwell, Hammond, Fife-Schaw, & Smith, 2006), so the content of the interviews changed as new themes were discovered and as the research direction was refined. The interviews focussed on the systems that the participants encountered in their professional practice. A conversational style was adopted to encourage the free exploration of the issues that the participants deemed to be important. However to ensure that the interviews centred on product changeability, a prompt sheet was used by the researcher, with a structure as follows:

- INTRODUCTION: Participant reminded about confidentiality and recording agreements then given background information about the study and researcher
- PART 1: Participant described background and job role at the company
- PART 2: Participant asked to choose a system and describe the influences that affect it in use
- PART 3: Participant asked if their system could change or be changed in response to those influences
- PART 4: The concepts of resilience, robustness, flexibility and adaptability introduced and discussed in relation to the participant's system

4.1.1 Sample

The types of systems discussed in the exploratory study were varied, including software, organisational, and hardware systems. The commonality between these systems was that they all related to a technological product or service. The sample spanned across domains but also at different levels of abstraction within a single domain, with the last eight interviews conducted with stakeholders from the automotive industry. Interviewees were recruited in three ways: through personal contacts, by asking colleagues for contacts and by emailing companies directly. The list of participants for each sample are given in Table 4-1. The exact job titles of the participants have been generalised to avoid the identification of individuals or companies.

Table 4-1: Participant list for exploratory study interviews.

PARTICIPANT ID	JOB TITLE	COMPANY SIZE (# people)	COMPANY AGE (years)*	SYSTEMS OF INTEREST**
E01	Head of Software	500-1000	15	Software product; process; software team
E02	Project Manager	500-1000	15	Process
E03	CEO and Founder	1-50	5	Organisation; hardware product
E04	CEO and Founder	1-50	5	Organisation; process; service product
E05	Engineering Manager	5000-10000	15	Software product; software team
E06	Engineering Manager	500-1000	30	Hardware product
E07	Research Manager	10000+	50	Hardware product; industry
E08	Chief Engineer	10000+	50	Hardware product
E09	Systems Engineer	1000-5000	30	Hardware product
E10	Engineering Analyst	10000+	50	Hardware product
E11	Data Analyst	500-1000	10	Service product
E12	Chief Engineer	10000+	100	Hardware product
E13	Founder & Advisor	1-50	10	Organisation; hardware product; society
E14	Design Manager	500-1000	20	Industry; hardware product; society

*rounded for anonymity
**given in order of most discussed

Participants were chosen to give a broad range of perspectives on changeability across different types of technical system and at different levels of abstraction. I used an iterative approach to sampling, analysing the interviews as I went so that the sample evolved as the study progressed and important themes emerged. This allowed me to get a good coverage of domains whilst making sure there were points of comparison across interviews. The systems discussed in the first six interviews were relatively small scale, including a software product (E05) and a start-up with few employees (E04). These participants (E01-E06) all held management positions within their organisations, so they had a good overview of their organisations and had an understanding of both social and technical factors. In the remainder of the sample group (E07-E14), the participants were chosen at different levels of abstraction within a single industry, the automotive industry. This meant that changeability of a single socio-technical system could be explored from different stakeholder perspectives, from those working on a specific component, to those working with an industry but outside of it.

The interview sample was chosen to span across domains and job roles. However, some commonalities were used so comparisons could be made across the interviews:

- Participants E01 and E02 worked in the same company
- Participants E03 and E04 both worked as CEOs of small, relatively new companies
- Participants E05 and E06 both worked as Engineering Managers
- Participants E07 to E14 were all stakeholders of the automotive industry

There were also key differences in the sample:

- Level of organisational abstraction: from those working on specific components (E09-E11) to those overseeing top-level systems (E07-E08, E12-E14)
- Primary area of system interest: either social (E07, E13-E14) or technical (E08-E12)
- Level of system innovation: from those working on novel products or research (E07, E11, E13-E14) to those working on existing legacy systems (E08-E10, E12)

This sampling approach was taken to offer an overview of the issues surrounding changeability and system lifecycle properties in industry, highlighting possible areas for further study. The distribution of the sample covered both social and technical systems as well as different levels of stakeholder abstraction. Figure 4-1 shows the participants ranked on the y-axis based on the proportion of each interview spent discussing social systems versus technical systems. The x-axis shows the levels of abstraction each participant discussed these systems at, which are defined as follows:

L1	component
L2	sub-system
L3	multiple sub-systems
L4	organisation
L5	multiple organisations
L6	industry
L7	country

The organisation that each participant worked for was taken as the base point for these levels of abstraction (L4). Systems that were within the organisational system (L1-L3) were considered to be at a lower level of abstraction, systems that contained that organisation (L5-L7) were considered to be a higher level of abstraction. Although both technical and social systems were referred to at all of these levels of abstraction, the majority of technical systems were discussed at L1-L3.

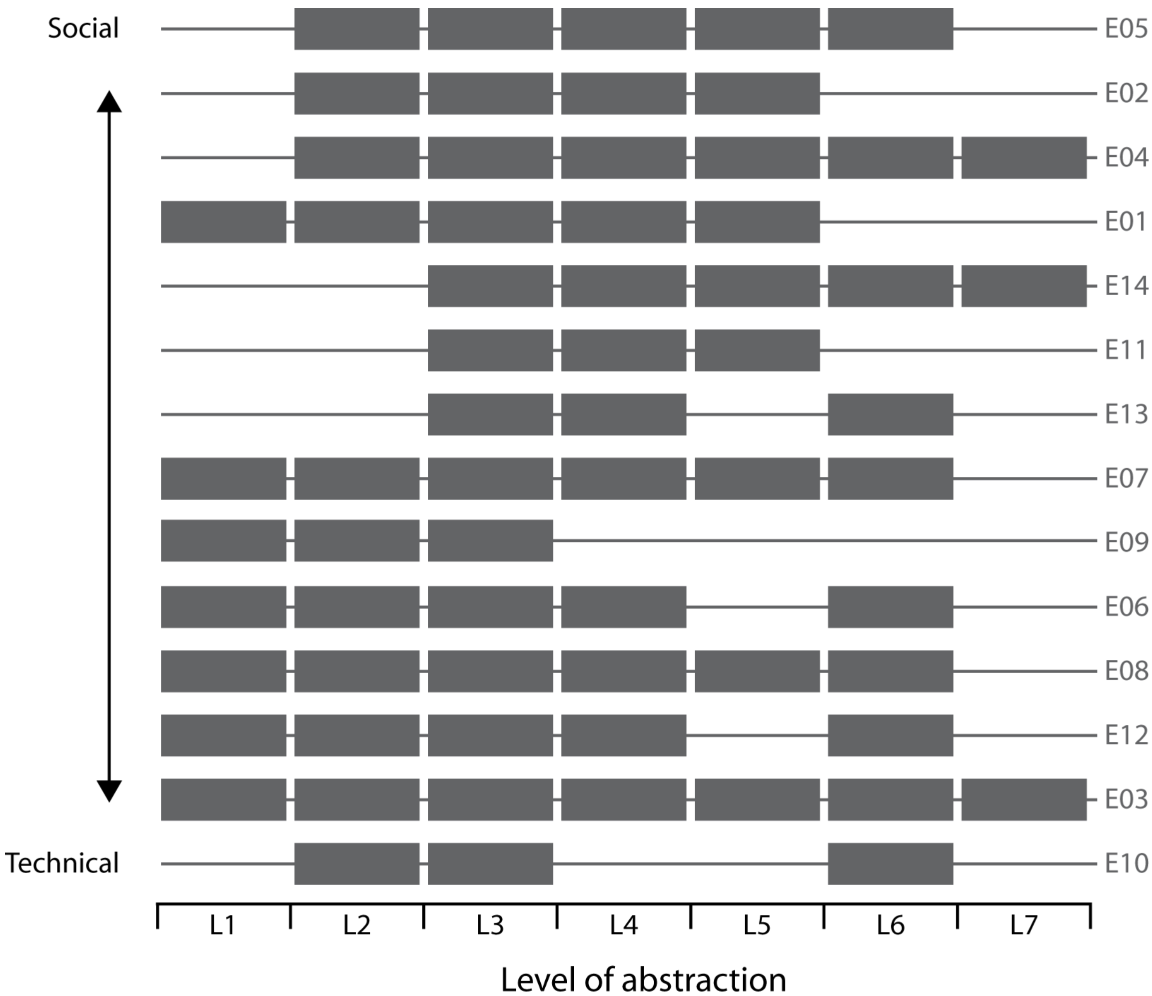


Figure 4-1: Figure showing the interview participants ranked by the proportion of social and technical systems discussed in the interviews, shown with the levels of abstraction these systems were discussed at.

The sample covers both technical and social systems. This is partly because the participants all had technical backgrounds but also most were mangers of some kind. Almost all of the participants thought about the organisation that they worked for (L4). It was more common for the stakeholders to talk about technical systems at lower levels of abstraction and social systems at higher levels of abstraction.

4.1.2 Data collection and analysis

The interviews were audio recorded with the participants' consent. The audio recordings were then transcribed verbatim as soon as possible after the interview, adding memos to the transcript for extra details such as hand gestures, or thoughts that occurred whilst conducting the interview. The transcripts totalled over 65,000 words. Hand written notes were also taken to increase engagement during the interview, indicating to the participant when a point was particularly valuable, and as a backup in case of problems with the recording. The transcripts were imported into qualitative data analysis software (Atlas.ti) and were coded using a general inductive approach to coding (see Section 3.7) (Thomas, 2006). After three iterative coding cycles, six themes emerged, which are presented in this chapter. The analysis was conducted on verbatim transcripts that included pauses, broken sentences and repetitions. However, the quotes that are used as part of this discussion may be edited versions of the original data to increase readability or maintain anonymity.

4.2 Findings on changeability in product systems

The products discussed in the exploratory study included a photovoltaic cell, a retail website, a personal transport service and cars. The products are all use some combination of software and hardware and therefore have a technical function and structure that will determine if and how the product is able to change. Product changeability is defined here as the ability of a product to change, once it is in service, to accommodate unexpected influences.

4.2.1 Motivations for product changeability

The general implication in the exploratory interview data is that most products (including hardware and software) are currently developed according to a set of requirements and do not change once in use. However, there is evidence of stakeholder motivations to build products that are able to change (or be changed). These motivations include changing product requirements and competitive gains.

Designing a product to meet a set of fixed requirements assumes that the requirements gathered at the beginning of the development process are correct throughout the life of a product. However, asking users to define requirements is problematic, with one participant describing how users change their demands.

> *'There's a person who's going to use this thing who doesn't know what they want but they put these requirements down. I might have written the requirement down, and read it back to them, then written a bit of software. Then they say, 'It's not what I want, I want something different now." – E01*

The participants (E01, E04, E05) partly attributed this problem to the difficulty of knowing what the best solution to a problem is at the beginning of a design process, even when the problem itself it well defined.

> *'The solutions guys face problems from a vague or wrong request from the customer. You have to explain to the customer that you understand they've got this problem, but that's not the solution. There's always an exploratory element to requirement gathering.' – E05*

Requirements are not just difficult to define, they change. These changes are not limited to the design process but continue once the product is in use. Not being able to change a product can lead to competitive losses if there is an influence outside of the stakeholder's control that affects a system's performance (E03, E06). One example given by a participant describes a hardware product that had to be taken off the market after a component could no longer be sourced.

> *'One of the components we use in a product was withdrawn from the market because the regulations have changed. So there's nobody manufacturing them and we can't sell one of our products' – E03*

In this case the product could not be changed to use a new component, which can cause competitive losses as well as negative emotional effects for stakeholders (E01, E12). Some participants described how they do not just think about whether a product can be changed but also, who is able to make the change (E01, E05, E07, E09). They described how users can get frustrated if they have to wait for product developers to make changes. To overcome this, products can be designed to allow the user to make changes, which can be a competitive advantage.

'We contrast ourselves with competitors that are not plastic and adaptable. And often their software is better than ours in certain ways but the big difference is, if a new regulatory requirement comes in, you can fix our product without waiting for your vendor to fix it for you. That's a big advantage for us.' – E05

In this quote, the word 'fix' is used to imply that the product is built upon and changed to meet a new regulatory requirement (as opposed to the product breaking and being restored to its previous functions). Another competitive advantage of this type is the introduction of disruptive technologies into a product (E06, E07, E10, E14). New technologies can be introduced by integrating them into existing products, rather than developing new products, which can save development time and cost especially for complex products with long lead times. It is not just software that is designed to change to meet the needs of users, hardware can also be flexible. In one example, a participant describes how a car was designed in this way to meet customer demand.

'In terms of flexibility, we wanted our car to be the Swiss Army knife that could do everything. It adds to the cost of the vehicle but people love it. We could easily do like other manufacturers, but no, we offer flexibility because people want it.' – E07

Some of the flexibility described above is designed into the original specification of the product. This type of flexibility does not contribute to product changeability because the product is only accommodating expected use conditions. But, the participant went on to describe how the 'Swiss army knife' car has had an unexpectedly long service life, partly because users make use of the vehicle features in ways the manufacturers did not expect, or design for.

Product changeability was deemed worthwhile if it solved a product issue (e.g. addressed a new requirement) or if it offered a competitive advantage. However, some interview participants also described barriers to achieving product changeability.

4.2.2 Disincentives for product changeability

For many of the interview participants, product changeability was not a familiar concept. In fact, for some, the interview was the first time they had reflected on the idea of actively designing products that can change, and identified existing examples in their system. The more established view of change appeared to be that products should be robust, resisting influences. If a product's operational tolerances are exceeded and it breaks, the product is repaired to the original specification. For cars, this approach was attributed to the safety criticality of the product and the high level of regulation (E08). Complex products like cars, are designed to be robust to expected variations in their service life, for example different environmental conditions in different countries. They are also designed under the assumption that a vehicle will have ongoing services and repairs through its design life. This means that service and repair costs are minimised. For example, one participant described how a bumper is designed to reduce the damage caused by an impact and subsequently reduce the cost of the car repair.

> *'Take a typical low speed rear impact. What you want to do is to contain the damage as much on the periphery of the vehicle as possible. There's a framework welded into the floor of the car, and what you don't want to do is damage the structure inside the car because that's a big repair. Optimally you'd contain the damage to bolt on pieces in the bumper beam itself.' – E08*

This requirement for robust design is driven by a business need to reduce the cost of the product throughout its lifecycle. Stakeholders have pressures from their organisations and the nature of the industry that they work in. For example, in the car industry, the most important factor for the product is the cost and performance trade-off.

> *'We are forced into designing the car to be optimum for now and for what we know. Maybe that's a short term way of thinking but that's also the commercial reality with the volumes that we've got. We have to justify to everybody why our car costs two cents more than the last car. We have to optimise for now and then try and accommodate in the future if there's change. I can imagine if you're in a much lower volume less financially critical industry that you could achieve flexibility much more readily.' – E12*

Product requirements are also driven by customer wants or needs and, as one participant pointed out, some types of product changeability may not be desirable. Sometimes products, in this case a sports car, have a clearly defined function and, achieving this function may make changeability unattainable or unnecessary.

> *'If a customer buys a car, maybe she doesn't want flexibility in it at all, she just wants a sports car that she gets in at the weekend, puts the roof down and drives like she stole it and enjoys it, likes to stroll round Stratford looking cool, and she doesn't want any flexibility in the product at all.' – E07*

Even when product changeability is desirable, the participants discussed the importance of trading-off changeability with other factors such as cost (E06, E07, E09), development time (E01) and safety (E08, E09). For example, engineers working on safety critical systems were particularly concerned with how to test a product that might change its behaviour in use. One participant described how changeability is designed into a car engine that could adapt itself to different driving conditions.

> *'So we already do a fair bit of adaptability where we need to but it's not easy because, you're never sure quite where it's going to go and so to test it properly is really hard. So there tends to be a few areas that are very well done, they've been done for years and you need them to be flexible. But, for engineers that's a last resort.' – E09*

To compound this issue of testing, some regulated products have to be recertified every time a change is made, so changes are avoided unless absolutely necessary (E03, E08, E12). This is especially true for hardware and is in contrast to earlier examples where changing regulations were an incentive to build changeable products. Situations where the benefits of product changeability are not seen can be overcome by improving stakeholder understanding, but there will still be cases where changeability is not desirable or possible.

4.2.3 Product structures that enable product changeability

For products, changeability appeared to be mainly determined by technical architecture decisions. Architectural attributes that enable product changeability were identified by participants, including modularity (E07, E08, E09, E11, E13), configurations (E01, E05, E09, E14), and platforms (E01, E05, E06, E07, E08, E10, E12). These attributes are defined as follows:

- Modularity is the extent to which elements of a system can be separated and recombined
- Configurations are the combination and organisation of a system's elements

- Platforms are the elements of a system which are shared by a large proportion of the system's other elements. Usually the platform has few or no variants (while other elements often do)

Technical architectural attributes were directly linked by the participants to the complexity of a system and how easy it was to change (E01, E03, E05). However, these product architectures were not necessarily designed with changeability in mind, they were determined by business decisions and social structures within the organisations (E01). For example, managers have a defined group of stakeholders they can directly influence. Therefore, modularity is used to simplify the interactions between groups and configurations are used to make interfacing two modules more straight forward.

Modularity

Most products, whether software, hardware and services, appear to have some degree of modularity. Modularity is used, to deal with the complexity of vehicle design. The specification of each module can be defined and assigned to a specific team of people. This is especially important considering that many parts in complex systems, such as the engines in vehicles, are now outsourced to specialised suppliers to save cost (E09, E13).

A modular product design may not be an optimised design. Modularity can introduce redundancy into a design. However, as one participant described, there can be compelling business drivers to use modularity. For example, if the development cost of a vehicle is too high for small volume applications, the manufacturers can instead design one flexible platform with modules for each application.

> *'The extreme of modularity is one of our products were we have something like 40 odd derivatives off a single vehicle. We have the ability to fit other items on the back of the vehicle so it becomes a pickup, it becomes a crane, and it becomes a military vehicle. This modularity does need a different design approach and you have to put redundancy in the product, so it's a compromised design. But if you want a large amount of variety at small volumes, you have to design the body differently because you can't afford a multi-million pound investment in small volumes.' – E07*

Modularity is also used to get commonality across different products. As one participant described, using the example of cars, having common parts leads to economies of scale and reduces the size of part lists. However, commonality can lead to structural inefficiencies. One way this problem is avoided is by designing parts for groups of similar products rather than a whole product range.

> *'I looked after the latches on the doors that keep the door closed. These latches are very expensive to tool up and you need lots of them. So we try and have a common latch that we use on lots of different models, because that way you get economy of scale. Another advantage is, if you can reduce the number of parts that you've got, you're actually helping the administrative burden of your system. However, there are downsides to commonality. If I've got a little car it's going to have little, light doors, and you only need a basic small latch. If I now try and put that latch on a big truck with really big and heavy doors, that light latch is going to break pretty quickly. Then, if I design the latch for the worst case, which is the big truck, when I put it on my little car it's massively over engineered, it's too big, it's too heavy, it's costly, it's just stupid. So what we try and do is group the usages and we have a light and a heavy.' – E12*

Part modularity can lead to time and cost savings however, it does not necessarily lead to increased product changeability. One participant expressed frustration over commonality in the regulated environment of the car industry. If there are many products using a single part, it can be difficult to change the design of that part.

> *'One downside of commonality is, if I want to change something on a part, I've got to go and get the agreement of everybody who uses it. And that isn't half difficult. You've got to get in touch with people that you've never heard of, who are in some manufacturing plant you've never heard of, building vehicles you've never heard of, but they're using your latch and they have to agree before you can change it. If my production line stops and I'm going to take six weeks to get approval from people around the world then that's quite a stressful thing.' – E12*

Another limitation to modularity is that not all systems can be modularised. One participant described how in vehicles, modularity is generally used at a high level of abstraction, and each module is still a complex, unique system.

> *'The headlight design isn't modular. The bulb might be modular, because that's part of the normal spare parts system, but actually the headlight is configured, along with every panel, every seat, and pretty much everything in a car. That's an interesting thing. Cars still struggle with the fact that although there's a very high level architecture – a platform, powertrain, body, innards – that within that, pretty much everything is unique.' – E13*

When separate groups of people are working on each module, the interfaces between them must be integrated seamlessly. Interfaces between modules can add cost, weight and complexity (E07, E09), but some interface problems can be resolved by having configurable modules (E01, E09).

Configurations

In the example above, the participant talks about configuring a headlight. Configurations are particularly important for systems where a module or a whole product are outsourced, because they allow a user to make changes easily. This can overcome problems when changing a standard part (as discussed above with the example of a latch). One participant described the configuration of car engine software. The configurations allow the software to be outsourced and tested with hardware to find the optimum performance.

> *'When I've have software made for me, the software writing is outsourced but then what arrives is very configurable. You deliberately request software that is flexible so that when you're testing in a car, you can try option A, B, or C, to see how they each work. But you have to think ahead to design what arrives, you need to define what option A, B and C are and how you switch between them. So you can be in a car and can say, oh I wonder what that does, oh that's cool we'll keep that or like that doesn't work or whatever. We find that works, but you can't do anything too dangerous or really stupid.' – E09*

In the example above, two of the options A, B and C may not be used in the final product. It not clear whether the software is just configured once or if it is *reconfigurable.* This configuration occurs before the product (the car) is put into service, but for a reconfigurable product the principle also applies to making changes to a product once in use. Another participant described how automotive manufacturers are learning from the consumer market, building flexible hardware that can be reconfigured using software.

> *'The current paradigm for iPhones and Android phones is to have an interface that's infinitely flexible and reconfigurable. I think that when you hear from car manufacturers that the future is button-less, what they're seeing is the appeal to reconfigure things through software and manage less hardware screens.' – E14*

In the engine software example, configurability is built into the system using redundancy (a choice of three options). However, in the button-less interface example, configurability is achieved whilst reducing the amount of required hardware. Also, in the first example, change is limited to a set of options that were defined in the design specification whereas, phones can be reconfigured at any point in their design life by making changes to the software.

Platforms

Platforms are essentially complex, configurable modules. They are complex, with many interconnected parts, therefore, making one change can spiral into many. For this reason, only minor adjustments are made to a platform once it has been designed (E12). In automotive design for example, most of the underlying technical functionality is designed as an integrated system, or platform, which is time consuming to design and very difficult to change. One participant described how current levels of configurability for car platforms are seen as revolutionary.

> *'We're now designing chassis so that the wheels can be changed to be six centimetres further apart longitudinally. Quite honestly if you did that 25 years ago, you would start with a new piece of paper because it was not possible to take an old design and stretch it six centimetres. That's how optimised they were for a particular car, it's crazy. From the perspective of insiders who have gone through those decades of change, those are really big changes. From the perspective of an outsider like myself, but a very interested outsider who studies the automotive industry, they've done nothing. I'm sorry but it's a car. Your business model hasn't changed and the blinking car hasn't changed. The level of innovation, the level of adaptability, modularity, flexibility, whatever, is tiny.' – E13*

In the case of car platforms, small adjustments are possible but the main changes that the user sees is designed as a separate, less complex module. These modules are called 'top hats'. The top hats contain parts of the car that must change more regularly to meet changing requirements, but most of the architecture of the product cannot change until a new platform is developed.

'From time to time you have the opportunity to make a new platform because there's a finite lifetime on the scalability and operating envelope of each platform. When you're making a new platform you try and consider all future models that you're likely to build on that platform and try and build in a sufficiently broad operating envelope to accommodate all of those future models. Business is better, in terms of return on investment, if you can stretch out the life of a platform, but a platform will typically last around 12 to 15 years.' – E08

Using platforms enables change whilst minimising the investment cost in new products. However, these platforms must be designed to accommodate future changes that might be difficult to predict, which leads to a trade-off between optimisation and changeability. There was evidence of this trade-off in both software and hardware products.

'Because we're producing a platform for people to build things on, you're trying to be all things to all people. You're not trying to specialise too much in one thing because you don't know what people are going to do.' – E05

'When you're developing the platform you have to try and find the most efficient design solution that you can to cater for what you're going to do now and protect yourself for the future as well. So you design around what you know which may be the next six years and then, in the second six years of the platform's life, the top hats have got to fit in with the platform.' – E12

To be able to change in the future, platforms must be designed with 'wide roads', to accommodate future upgrades. For example, hardware that can accommodate more cables if the electrical architecture of a vehicle is updated to support new modules (E08), or new technologies including hybrid electrical vehicles (E10).

4.3 Findings on changeability in socio-technical systems

Product changeability was identified by the participants but it was primarily a side effect of business drivers not related to resilience. Participants did however identify other ways that systems can change in response to unpredictable influences. These other types of changeability were related to social systems, not just technical product systems. In this section I discuss these different types of socio-technical changeability as well as the effect of stakeholder perspectives on understanding changeability and the importance of communication between stakeholders.

All of the participants, except E13 and E14, were stakeholders working to deliver a product for organisational profit. Organisations were therefore the most discussed socio-technical system in the interviews, with specific industries sometimes referred to. However, it is expected that the socio-technical themes discussed in this section are transferrable across to other socio-technical systems, such as cities, and not just other for-profit organisations.

4.3.1 Types of socio-technical system changeability

For the most part, the participants identified changeability in systems involved in *developing* products, rather than the products themselves. These other types of changeability can complement product changeability, overcoming the limitations of building products when future influences are unknown. One participant described this design decision in the context of software. Building flexibility into software, using configurations, can increase development time, future risk and architectural complexity. Therefore, the participant argued that in some cases, the flexibility should be pushed into the development process.

> *'We're trying two ways to be changeable. We're trying to design software that is adaptable and changeable and also we're trying to have software development processes that are agile and reactive. And I like the agile where you don't make the software agile, you make the process agile, because there are lots of cases when people have built in imagined, desired flexibility and need for change and spent years putting in stuff that never gets used.'* – E01

Here the decision is not whether change will be needed in the future, but whether changeability should be built into the process or the product. In fact, one of the reasons changeable processes like Agile development work well for software is because software products have some inherent flexibility. Software is written in modules of code, which can be easily changed and updated in service. This means that the changeability does not have to be configurable.

Process changeability emerged as an interesting area of discussion because most of the participants had some level of control over a process sub-system, usually more control than for product sub-systems. The participant's roles included managing a process (E01, E04, E05, E07, E08, E09, E12, E13), designing a process (E02, E03, E10) or designing a system to improve a process (E06, E11). The processes discussed included the development of new operational systems and the management of teams of people. Evidence was found in the interviews that stakeholders are already using popular methodologies, including *Lean* (originating in manufacturing (Ries, 2011)) and *Agile* (originating in software development (Martin, 2003)), to enable change through the development process (E01, E02, E04 and E05).

> *'We look at change and ask how we can maximise our ability to get change with the same team and the same cost. Of course the Agile process is one way.' – E01*

These methodologies are not used as a strict set of rules (E04, E05). In fact, the participants said they used them as a set of guidelines, picking and choosing the parts that fit their organisation and way of working.

> *'We started doing agile software development some years ago and it's been through a number of internal evolutions. We were a bit picky and choosy about which parts and which processes to use because I'm not in love with the idea of people having found the received wisdom and people just swallowing it whole. Engineering is much more complicated than that and you need to exercise judgement always.' – E05*

The main advantage of process methodologies appears to be that they enable fast, continuous feedback and iteration. A process is built that produces the minimum viable product, which is tested and then iterated based on how the product performs. The main advantage of this approach, in terms of building resilience, is that it concentrates on being able to adapt in response to influences that occur during the development process, instead of trying to predict what will happen.

> *'I'm sure in many cases there's too much planning and too much hesitation and not enough of a feedback loop. They just plan the whole thing, whereas, they could do something small, see how it went, and do something else, and do something else.' – E01*

Agile and Lean methodologies are designed to accommodate uncertainty in design and development processes. However, process systems are relatively controlled, with their available resources, approximate lifespans and purposes all well-defined. It is also worth noting that these methodologies are being adopted by certain groups of stakeholders including software developers and start-up CEOs. Not all stakeholders are receptive to these new attitudes towards uncertainty and change, especially for traditional processes in manufacturing that require significant upfront investments in hardware (E03, E06, E13), and even within companies where changeable processes have shown to be effective (E01, E02).

Within a socio-technical system there are sub-systems that are not able to change. These can be product systems, or groups of people who are not receptive to change. What appears to be important is that the sub-systems that adopt a resist and recover approach can interface with more changeable systems. These types of interface were seen between different types of systems in the interviews, including:

- Groups of people within a company (e.g. E02's team interfacing with E01's team to make their software system more changeable)
- Software and hardware (e.g. E07 wanting to change the performance of car hardware in service with on-the-fly software updates)
- Companies across different industries (e.g. E11's organisation using cars as one part of a car sharing scheme)

These interfaces may result from a technical architecture but the changeability usually comes from the actions of people. In one example, a participant described how they were developing cars to interface with consumer products. In this way, the product could integrate new ideas from faster moving markets, without changing its core product offering.

> *'We can never keep up with the consumer products that are much smaller and have a much faster refresh time, and that's okay. You have your latest technology on your phone with the latest updates. So we don't try and chase that and compete with it because the phone manufacturers are much more nimble and able. That software is their everything, it's their business, and it's their lifeblood. So we just use our screen as a mirror and then that takes us right out of the critical path and it allows us to make sure the consumers have what they want.' – E07*

In this example, the car and the mobile phone are not changeable products. The changeability in the system comes from the fast development process for mobile phones, which is essentially down to how fast the people in the company iterate. In fact, in most examples from the interviews, it was the flexibility and adaptability of people in systems that led to changeability. Even when considering product structures that lead to changeability, most products still required people to make decisions about when and how to change modules, configurations and platforms.

4.3.2 The role of social systems in socio-technical changeability

It was clear from the interviews that people act both as barriers to and agents of change in socio-technical systems. Social system change happens on both a micro and macro scale. For example, one participant described how as a start-up grows and the number of employees increases, the organisational structure changes, which affects the company's ability to change.

> *'If you read a lot of stuff about systems in terms of people, there are natural points where things change and structures change. So companies do change. The question is, how do you still get innovative, fast moving bits within an organisation when you go to lots of people?' – E04*

There is interplay between changes happening at different levels within social systems. This is compounded by the complexity of individual stakeholders. These individuals can be thought of as equivalent to components in technical systems but components are generally well understood and reducible in a way that people are not. For example, as an organisation grows, changes in the system structure can change the outlook of individual stakeholders and therefore affect the quality of communication in the system.

> *'As a start-up things are really quite simple, they don't seem like it at the time but they really are. The layers of hierarchy are very shallow. When we were acquired we were 17 people all up. At that point I could have a row with the CEO without any trouble. But in a larger company the personal dynamics are just so different, it's just a nightmare. You're dealing with people that you don't know very well typically and that has far more effect than I think is reasonable.' – E05*

This change in outlook also occurs on a local level. One participant described how changing a technical development process, affected both the perspective and resulting behaviour of software developers in an organisation.

> *'In the old fashion days, you'd work towards a release of your software, which you might do every quarter and put it on a disc and send it out by the lorry load. But now we release 300 changes every day so it's just going out all the time and that's much better, because there's a lot of human behaviour that goes around the long release that we hate. The human behaviour is that, 'If I'm going to wait another two months for the next release, I'm going to get my thing squeezed in here. I'm going to get very anxious and stress and push and disrupt the development process to get my thing in this release', which is annoying. But if we are doing a release every day they think, 'Oh I don't care if I miss today's, I'll get it in tomorrow." – E01*

This issue is complex because the level of overall system change is affected by both the ease with which technical sub-systems can be changed, the ability of social systems to change, and also the interconnections between the two. For example, one participant argued that the structure of the technical system (in this case, software) is a limiting factor in changeability, but other participants said it is people that limit change.

> *'We have too much of an obsession with the process but I think we don't consider that architecture enough. We don't consider the complexity of the software itself as being a factor in how fast we can change. You see these small companies of five people outpacing fifty. How do they do that? It's usually because the thing the five are using is simpler and the thing than fifty have has grown to be a great complex nightmare. They have all the problems of intercommunicating as well but the thing that they're dealing with is neater so they can change it more easily.' – E01*

Considering how architecture and structure affect changeability is just as important for social systems as it is for technical systems. In the interviews, modularity was the main structural feature that was evident in social systems. In organisations, larger social groups are modularised into specialist departments and business areas. The interfaces between these modules can be important, just as they are for technical product architectures. One participant described how having well defined social interfaces was desirable because social interactions are complex. The interface they described was between two departments in a company, one of which was designing and building software for the other.

'Our software is for an internal consumer so our customers are very near and we don't have money related contracts. But there's a temptation I think to live in a contractual world where you can just call on a consultant and say, 'I'm going to pay you £100 and you're going to deliver something that's this and then I've got money hanging over you and you have to do it for me because I'm paying.' There's an element of comfort about that relationship whereas in this one you have to go and deal with those difficult IT people who may not do what you say and you don't have the power of money over them.' – E01

Social interfaces are largely determined by organisational structure, which in turn is influenced by the architectures of technical systems. For example, the architecture of a manufacturing line is distinct but related to the architecture of a product that is produced on that line. The two systems are usually run by different teams who have to talk to one another. The boundaries between technical systems are also hierarchical, for example, an engineer responsible for the doors of a car will be running a sub-system within the area of body engineering.

The two participants (E01 and E05) who were using agile software development, understood the issues associated with crossing these social and technical system boundaries. They talked about the benefits of other groups of people being able to change their technical system, but also emphasised the need to control these changes.

'Users will come to us and ask us to change something but I'm busy doing other things. That's where a bit of configurability comes in, because they can now solve their own problems. But this needs to be kept in balance because you're effectively giving them the ability to change something from the standard. Maybe the person who did the configuration leaves or maybe they forget what they did. If you give them too much room, they'll engineer themselves into the same tar pit that you're trying, with all your software team techniques, not to do.' – E01

In some cases, technical systems can be designed in a way that optimises the changes made by people. This can avoid unnecessarily increasing the complexity of the technical system when changes are made. For example, if a software platform is designed so that the complexity is contained to the main platform, then changes can be made to add-on modules without jeopardising the main system.

'We can talk about two systems, the platform and what people build on top the platform. They are very different in terms of their structure. You kind of push the complexity into our platform rather than adopting it yourselves. Which has a couple of benefits, one is I think we're typically more talented than our customers, but also, we can be far more disciplined about how much we test.' – E05

This approach to platform design also constrains who in the social systems can make which types of changes.

'We impose constraints on people and say, you have to build your system this. By forcing them to do it this way they automatically get a distributed system whether they like it or not. Whereas with lots of other programming platforms, it's very easy for everything to get intimate with each other and you get a horrible mess and you get a system that's brittle, that can't be changed very easily.' – E05

Whether changes happen in technical silos or across sub-system boundaries, the most common barrier to achieving system changeability appeared to be communication. This is partly because changeability concepts are difficult to communicate. Communication issues can originate from physical separation, for example the geographical locations of stakeholders (E02, E05, E12), or from differences in stakeholder perspectives, for example, stakeholders using domain-specific diagrammatic representations and terminology (E01).

Some stakeholders are reluctant to consider ideas related to change because they work in high pressure situations where reliability is hugely important. One participant was designing supply chain processes and trying to introduce more changeability. Part of this process involved engaging stakeholders with different job roles and perspectives, who had different degrees of receptiveness to these new ideas.

'People in the production environment often understand process change. The sales people don't and they have no patience for it. I really have to work a lot on getting that message through to the sales and logistics people just because the pressure on them is so high if something goes wrong.' – E02

Technical systems are for the most part designed, modelled and tested methodically and rigorously. However, social systems are much harder to design and control. Some of the participants who were working in technical roles saw social systems as a negative influence on change, rather than an opportunity for the overall system to be more able to change.

> *'Some challenges are hard to model with an engineering approach because they just rely on humans communicating with humans in time. I guess the earlier the communication happens, the more flexibility we have in terms of our response, but in the worst case scenario when we don't get much notice then there's very little we can do to mitigate adverse consequences.' – E11*

Resilient socio-technical systems require both technical and social sub-systems that are able to change, but social systems are clearly complex, hard to understand and hard to control. Communication between stakeholders is important to manage this complexity and engage stakeholders with concepts of changeability.

4.3.3 The effect of stakeholder perspectives on socio-technical changeability

Each interview participant had a unique perspective on changeability. Some participants saw change as both necessary and desirable whereas others saw change as something to be avoided. The stakeholders' attitudes were informed by the nature of their role within their organisation and by business drivers. Therefore, stakeholders working on the same system had different viewpoints. These differences in perspective were particularly evident from the two participants (E01 and E02) who worked in the same company on related systems. For instance, one stakeholder (E01), running a team of software developers, described other people in the company as agents who instigate change. In this case the amount of change actually possible was limited by the amount of time the software developers had to build the changes:

> *'The external change agents are all of the people in the company who want changes, and there's a massive gap between demand and supply unfortunately. That causes all kinds of angst, grief and craziness.' – E01*

Another participant (E02) who worked in the same company had a different view of this supply and demand problem. This stakeholder described how they had found other ways to change their process systems, without changing the software. What the first stakeholder describes as 'angst, grief and craziness' is actually an influence on another system in the organisation to find a new way to change (i.e. they change without changing the software system):

> *'So if (Participant E01)'s team need to change something, it can take up to a year for it to happen. Often, when you go and see them and say, 'We need a software change.' they say, 'We'll put it in the pipeline.' but the change won't happen. So when we make changes, we ask if it will require a software change. If the answer is yes, we ask if there is a way we can do it without software changes. A lot of our processes then end up being quite manual.' – E02*

This example shows how two stakeholders can have different perspectives on the same product system. The team of software engineers see the process system manager as a change agent for the software system. However, from the perspective of the process system manager, it is better to limit software changes to get overall system change.

Another difference in the perspectives of these two stakeholders is highlighted by their responses to the introduction of new systems, in the form of acquired companies. One of the participants (E01) saw these acquisitions as potential agents that could enable the software systems to change. However, the other participant (E02) saw the acquisitions as a negative influence on the process systems, limiting potential for change.

> *'The company has been on a bit of an acquisition trail, so we've bought companies and they had their own IT crew and teams, but not our systems. We haven't wanted to stamp our systems all over them but we do want to get data to flow between us. We'd like it so that their software engineers could write something interfacing with ours. So they might be some of the external change agents.' – E01*

> *'It doesn't help that we've acquired quite a few companies, so the systems we use in different parts of the world are completely different and they don't talk to each other.' – E02*

These differences in perspective lead to different understandings of changeability. For example, the first participant (E01) might push for further acquisitions to increase the ability of the software system to change. However, the second participant (E02) might oppose further acquisitions or push for the universal adoption of existing technical systems. What is not clear in the data is how aware the stakeholders are of each other's perspectives. One participant argued that system change can be limited if stakeholders are unable to see beyond their own perspective.

> *'One of your problems with the car industry is actually so many things don't change. There is an enormous architecture but nobody recognises it as an architecture because they are just fixed points in those people's existence. And they don't realise that they could change those fixed points. They just go, no, no, no that's the way it is.' – E13*

The participants who had worked in more than one role at different levels of abstraction generally had a broader perspective and understood the importance of systems level issues like interface and architecture design. Conversely, some stakeholders found it difficult to understand the system from other stakeholders' perspectives, relying on top down requirements and bottom up incremental innovation in their specialist area. This approach is perhaps necessary to efficiently manage the design and manufacture of complex products, like cars, but limits the scope for disruptive change.

> *'As a supplier of one part into the system you don't really see beyond your part very much because there's just an interface that you're given to comply with. But as the system designer, you're also the customer. You have all sorts of things coming in to you and so you can to a certain extent decided how they are all going to fit together and how they're going to talk to each other. So as a system designer you have a totally different viewpoint and much more visibility.' – E09*

The participants' perspectives were not just determined by their role or position in an organisation but also more complex social factors such as belonging and identity. One participant was working in a start-up that was acquired by a large corporation. They felt as though they still belonged with their colleagues from the start-up, which was now a sub-system of the larger company. However, the participant felt pressure to change their perspective and act as an external stakeholder to the start-up.

> *'You have split personalities because you are different things. In some conversations I'm the [A] guy and in some conversations I'm the [B] guy. And I find that in the [B] conversations I need to learn to call [A] 'them', because I'm not 'them'.' – E05*

Stakeholder perspectives are neither trivial nor straightforward, with both technical and social influences. Perspectives should be explored by talking to individuals about their experiences and outlook on a system rather than assumed by their role in an organisation. This is important because all stakeholders have the potential to influence the resilience of a socio-technical system. Also, by understanding and comparing the perspectives of individual stakeholders, we can better understand how to communicate and talk about resilience in a way that is relevant to those working at multiple levels of abstraction in a socio-technical system.

4.4 Study 1 summary

RQ2: *What can we understand about resilience from its relationship with changeability?*

In Study 1, I have shown that although work has been done to break down and structure changeability concepts for technical systems, it is difficult to talk about change with stakeholders. Instead, these conversations turned to broader issues around resilience such as, whether changeability is a desirable lifecycle property and how social systems act as change agents. Before we can talk about the specifics of changeability at a technical system level, we must first have the tools to communicate about resilience in socio-technical systems.

When discussing product changeability, the terminology used by the interview participants was varied and imprecise. They did however understand the essence of concepts like flexibility, adaptability and robustness, and these terms helped to start a conversation. Not many of the participants had actively thought about designing products that are able to change proactively in use. Rather they talked about reacting – being forced to change products, or recover from influences.

The instances of product changeability that were identified in the interviews were not generally associated with resilience. Rather, this changeability was a by-product of some other business requirement. It can be difficult to justify product changeability as a design strategy because the benefits are long-term and difficult to predict. This is especially true for hardware products, which have high investment costs. For some products, like cars, requirements are systematically defined, accumulated over many years and used as a check list to ensure each product meets industry functional and quality standards (E06). These requirements ensure that cars are optimised to maximise their performance under tight budgeting constraints. However, creating a legacy of fixed requirements also means that making changes to the product is difficult in the development process and especially in use. The lack of change is compounded by long lead times. Whereas some new models of consumer goods can be released in six months, new models of cars take four years to develop. As the pace of change increases across many industries, stakeholders are increasingly motivated to build the capacity to change into systems so that new or previously unknown requirements can be accommodated in the future.

From the interviews, three product architectures were identified that may enable changeability: modularity, configurations, and platforms. Understanding how system architectures relate to changeability is important, not just for designing changeability into systems, but also in communicating about resilience to stakeholders. Defining a system architecture reveals how individual stakeholders perceive a system and which sub-systems they can influence. Products are just one type of sub-system in larger socio-technical systems, where other sub-systems include the processes and groups of people that design and develop those products. In the interviews, participants linked the ability of product systems to change, and the desirability of this change, to other sub-systems and socio-technical issues. It appears that to understand the resilience of a system, product changeability cannot be discussed in isolation to the systems that make and use that product.

This study suggests that some sub-systems in a socio-technical system, including many products, are designed to resist and recover influences rather than to be able to change. The way that overall system resilience is achieved is by these unchanging sub-systems interfacing with changeable sub-systems. For example, software can adapt to give hardware larger operational tolerances, or processes can adapt to produce new products. From the interviews it seems that most sub-systems that enable system changeability are social; groups of people or individuals who respond quickly to new influences and make changes or build new sub-systems.

One important finding from this study is that each stakeholder had a unique perspective on their socio-technical system. Differences in perspective were particularly evident when comparing data from two stakeholders of the same system (e.g. an organisation or industry). Insights into resilience were gained from looking across stakeholder perspectives however such comparisons were limited by barriers to communication about concepts related to resilience.

From this study it appeared that changeability needs to be explored in the broader context of resilience, considering the perspectives of multiple stakeholders across both social and technical systems. However, there was a communication barrier, which would make communicating with such stakeholders difficult. Therefore, in the next study, Study 2, I studied stakeholders across both social and technical domains who already had an understanding of resilience and were used to having conversations about systems faced with influences.

5 Understanding resilience through communication between stakeholders

Study 1 demonstrated that the concept of changeability is not well understood in industry. However that study also showed that some parts of complex socio-technical systems are either difficult to change or need to stay the same. Therefore, it is more useful to talk about changeability in the broader context of resilience. Resilience is a property that is more usefully defined at a higher system level than a product level. A resilient system has some sub-systems that are changeable and some sub-systems that are robust, with both properties contributing towards the system's overall resilience.

To better understand how resilience is interpreted in socio-technical systems and how it might be communicated effectively with stakeholders, a workshop was held with experts concerned with the resilience in systems across domains. 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 the commonalities and differences were observed between how the stakeholders communicated about resilience. This section of the thesis 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. As such, this study answers RQ3:

What can we understand about resilience through communication between stakeholders?

The workshop analysed in this study was organised by my supervisor Dr Nathan Crilly at the point in my research when I was trying to work out what the relationship was between changeability and resilience. We were talking a lot about whether resilience is an umbrella term for other system lifecycle properties. It also appeared that resilience was the most widely used system lifecycle property term in the field of policy, and was currently generating a lot of interest. Therefore it was decided to make this the centre of the workshop.

5.1 Method

To explore questions about resilience, a workshop was organised by the Cambridge Engineering Design Centre (EDC) and the 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 discussion 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. My role in this workshop was primarily that of an observer. This allowed me to take extensive notes and reflect on what the stakeholders were discussing, which would have been difficult whilst also moderating (Robson, 2011). In the second half of the workshop, I spoke to the participants about my work on system lifecycle properties, prompting further discussions about change and 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 the discussion of findings for this study, examples are presented in both an abstract and a domain-specific form.

5.1.1 Sample

Table 5-1 summarises the workshop stakeholders by field of study and whether they work primarily in academia, policy or industry (many stakeholders crossed these boundaries).

Table 5-1: List of workshop stakeholders by field of study or practice.

PARTICIPANT 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 specific systems that the participants were concerned with were all socio-technical in nature but were of very different kinds and different aspects of them were emphasised. For example, they 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.

5.1.2 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 using a general inductive approach (Thomas, 2006) with findings emerging from the raw data. Themes were drawn out relating to what the participants were communicating about resilience and the difficulties they had experienced in doing this.

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 developed in Section 5.2 before being given in the original domain-specific context. The domain-specific examples are paraphrased from the workshop data and are referenced to with the Participant ID numbers (see Table 5-1). 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 and were arrived at by discussion.

Analysing the data revealed what stakeholders are trying to communicate when they talk about resilience (Section 5.3). The data also suggested ways in which communication about resilience can be improved (Section 5.4). 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. In some cases only the function of the system is shown because the structure of the system is unknown or unspecified.

5.2 Findings on developing a diagrammatic framework for resilience

To represent and abstract the system examples that the stakeholders gave in the workshop, a diagrammatic framework was developed based on findings from the workshop, on what needs to be communicated about resilience, and from the academic literature, on how to represent system lifecycle properties. In the literature, diagrams have been used by authors to communicate to an academic audience (see Section 2.2), however no existing diagrammatic frameworks were intended for communication with system stakeholders across different domains. The literature review of lifecycle property diagrams highlighted the following actionable points:

- A single framework is needed to describe, distinguish and relate a set of lifecycle properties.
- The framework should be general enough that it is transferable to different types of system. Reliance on domain-specific terms should be avoided to reduce confusion between domains.
- The framework should show both structural and functional changeability.
- The framework should represent the system hierarchy so the system boundary and super-/sub- systems can be clearly defined. This means a stakeholder's frame of reference and the level of system abstraction can be established.
- Three features that characterise lifecycle properties should be included in the framework: system stimulus, response and value delivery.

5.2.1 System structure

The structural aspects of the framework are shown in Figure 5-1. 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. 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.

The system structure is shown using three levels of abstraction: *super-system*, *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 & Rechtin, 2009).

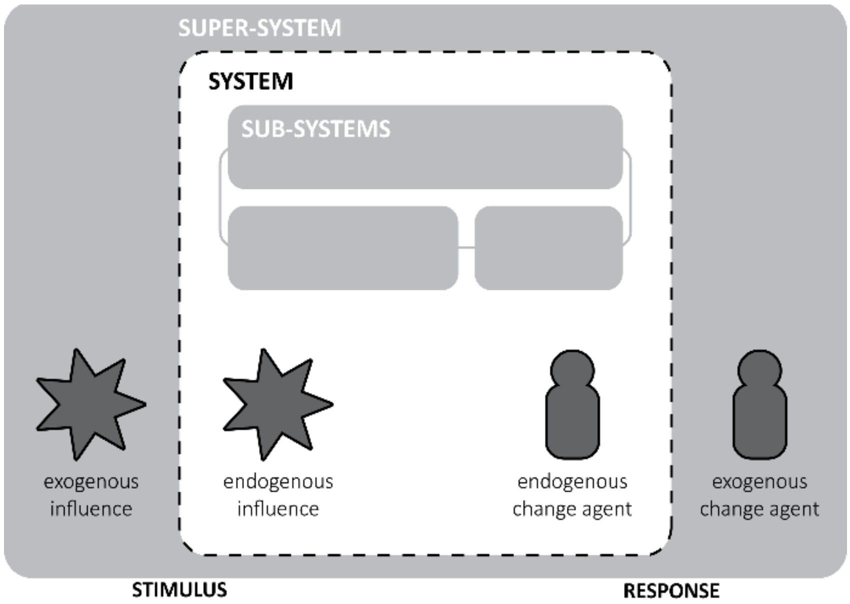


Figure 5-1: Hierarchical graphical representation of a system showing stimulus and response.

The terms used here to distinguish between stimuli and responses were inspired by the classifications used in the systems engineering literature (see e.g. Ross et al. 2008). Although these terms were useful for creating a diagrammatic framework, they are not carried through this research. This is because the terms 'stimulus' and 'response' were confusing for stakeholders so I instead moved towards using 'influence' for things that affect a system and 'response' for ways the system reacted to influences. This is also true of the terms 'exogenous' and 'endogenous', which were replaced in conversation with 'external' or 'outside' and 'internal' or 'inside'.

A set of lifecycle properties based on the structural aspects of the framework is shown in Table 5-2. 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, I 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 5-2: Framework for structural representations of system lifecycle properties.

	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 *robustness*.
	An exogenous influence affects the system. An external change agent responds to the influence, enabling a system change. This is referred to as *flexibility*.
	As above, an external change agent enables system change but the influence in this case is endogenous. This is also considered to be *flexibility*. Although a distinction is not generally made between the two cases, it may be useful to do so.
	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 *adaptability*.
	As above but with an endogenous influence. Also referred to as *adaptability*.

5.2.2 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 5-2a), the value delivery changes temporarily (Figure 5-2b) or the value delivery changes permanently (Figure 5-2c).

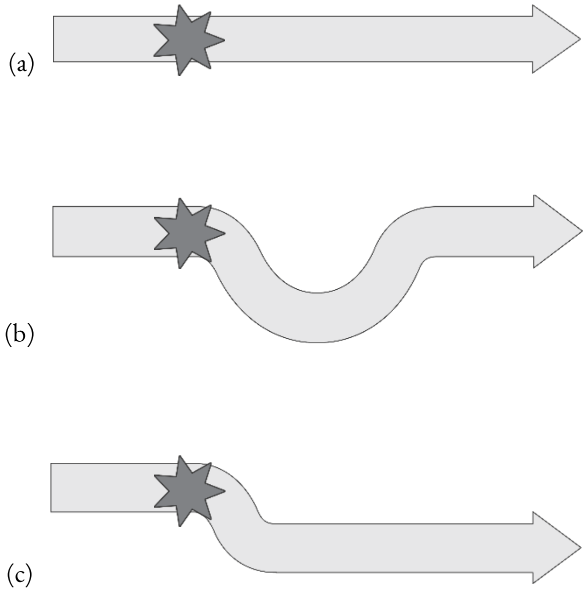


Figure 5-2: Arrows showing the function of the system progressing through time as the system (a) resists an influence, (b) recovers from an influence and (c) changes in response to an influence.

5.2.3 Combined framework

Representing both the structural and functional aspects of changeability can be done using the combined framework shown in Figure 5-3. 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).

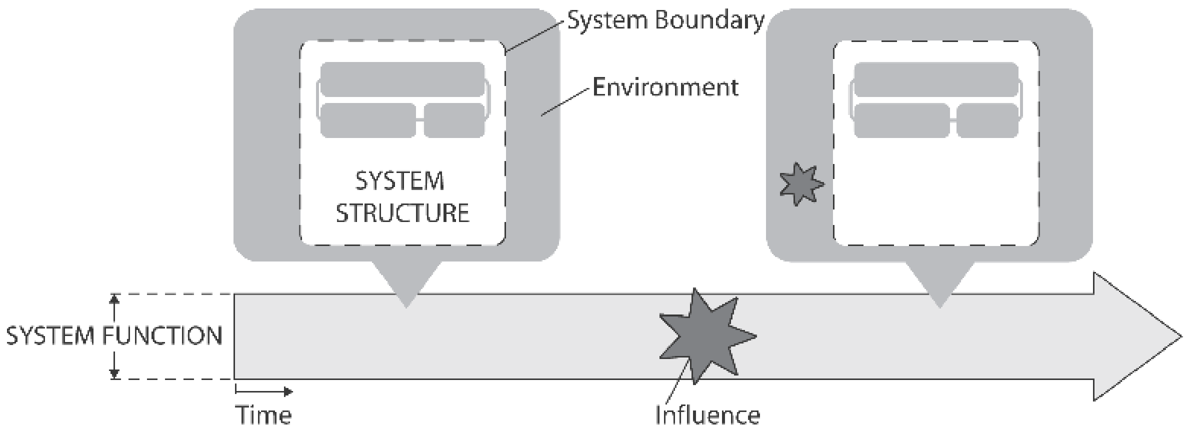


Figure 5-3: Combined framework showing the system structure and function.

This framework is applied in this chapter to illustrate system examples given by stakeholders in the workshop. Using the framework, I have been able to abstract from domain-specific examples and provide generic illustrations of resilience characteristics, showing how system structures and functions respond to influences. Each example is described in this abstract form, then a diagram is given, before linking the example back to the original domain context. The diagrams used in the main analysis of this chapter use this framework loosely. I found that real life examples given by stakeholders had important nuances that required a flexible diagramming approach. For example, in later diagrams, circles are used instead of rectangles to represent system boundaries because this was the clearest way to show multiple systems in a single call-out box.

5.3 Findings on 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:

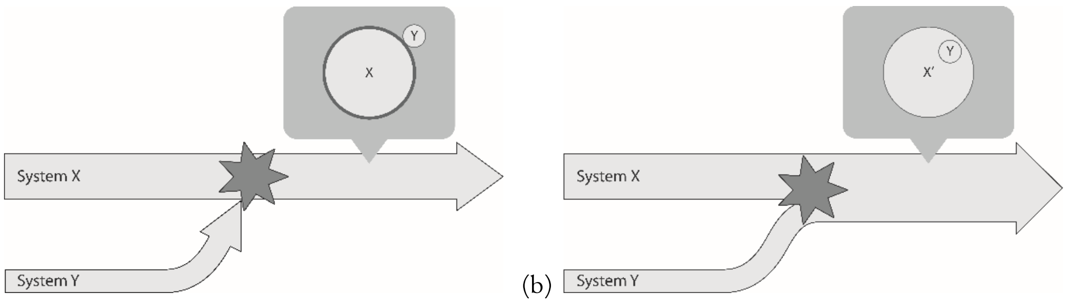
- R1: Resilience as *resisting* influences
- R2: Resilience as *recovering* from influences
- R3: Resilience as *changing* to accommodate influences

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.

5.3.1 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 functions and the purpose of the system may change.



(a) (b)

Figure 5-4: Diagram showing system X (a) resisting the influence of system Y and (b) changing to accommodate system Y as a new subsystem.

> Example 1a in the context of social sciences: 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).

In Example 1, system X could represent a society that resists changing to accept incoming people (Figure 5-4a), 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 5-4b). 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).

5.3.2 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 (P_1 and P_2), which, at 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, P_2. Once the influence is no longer affecting the system, the system recovers to resume its previous state, fulfilling both P_1 and P_2.

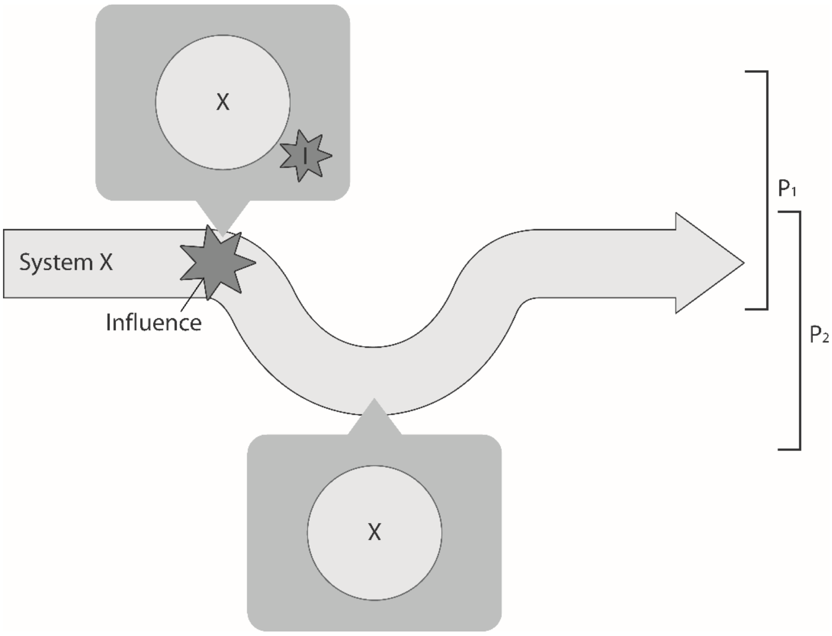


Figure 5-5: Diagram showing Example 2, a system (X) that responds to an influence by temporarily fulfilling one purpose (P_2). Once the influence is no longer affecting the system, the system recovers to the initial system state.

> Example 2 in the context of psychophysiology: An athlete (X) must sustain two purposes to be successful – mental wellbeing (P_1) and high levels of physical performance (P_2). 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)

In this example, an athlete's mental wellbeing is temporarily affected by a competitive sports event but recovers after the influence. The system (athlete) continues to function because it prioritises certain functions (physical performance) over others (mental wellbeing). The diagram in Figure 5-5 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).

5.3.3 Changing to accommodate influences (R3)

Traditional design approaches, focused 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 (C_1 – C_6). When an influence, I_1, 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 (I_2) of a different type damages one of the system components (C_6), the system can no longer function.

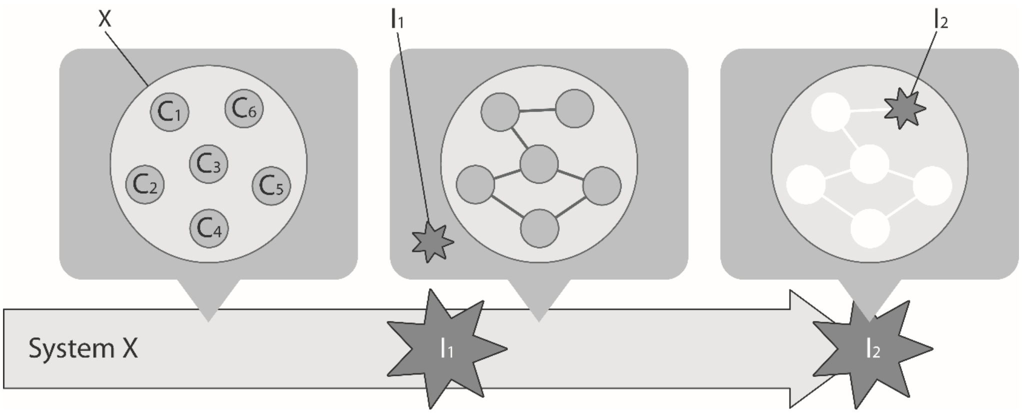


Figure 5-6: Diagram of Example 3 showing a system (X) where the structure is optimised in light of the first influence (I_1) to increase the system's robustness. When the system is influenced for the second time (I_2), the structure of the system does not allow the system to change to accommodate the influence so the system fails.

> 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 fall over. As engineers we 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)

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 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 comfortable under normal operational conditions, whereas changeable systems may be vulnerable but highly adaptable with the capacity for resilience.

5.4 Findings on 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 perspective.

5.4.1 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 where the boundary is defined.

> Example 4: System X consists of two sub-systems (X_1 and X_2). When an influence (I) affects system X, one sub-system survives (X_1) but the other sub-system stops functioning (X_2). System X_2 is not resilient to the influence but systems X and X_1 are resilient.

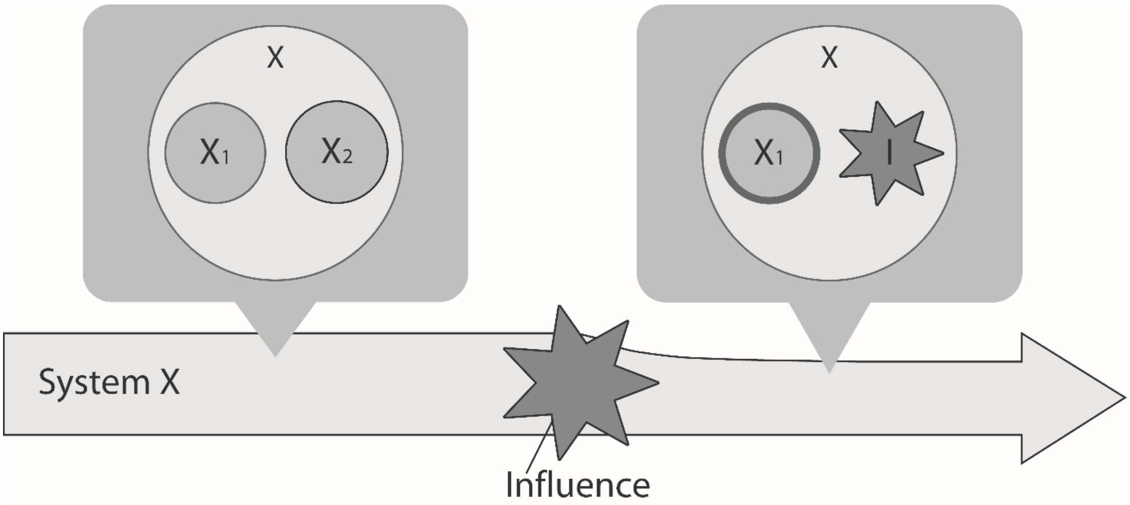


Figure 5-7: Diagram of Example 4 showing the resilience of system X when affected by an influence (I).

> 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 and can be treated with penicillin (I). However, over time some of these organisms have developed into Methicillin-resistant Staphylococcus aureus (MRSA). MRSA (X_1) is not any more virulent than other SA organisms (X_2) 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)

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).

5.4.2 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 (P_2) despite setbacks to their mental wellbeing (P_1); or the way a person maintains high levels of mental wellbeing despite setbacks to their physical performance (the second case is the reverse of the first case i.e. Figure 5-5 could represent both situations with the purposes, P_1 and P_2, 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 to get resilience (P03).

5.4.3 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 (X_1, X_2 and X_3). Defining the purpose of these systems is dependent on the perspective of the stakeholder. At a high enough level of abstraction, X_1, X_2 and X_3 might appear to have the same purpose, P_1, which encompasses P_2 and P_3.

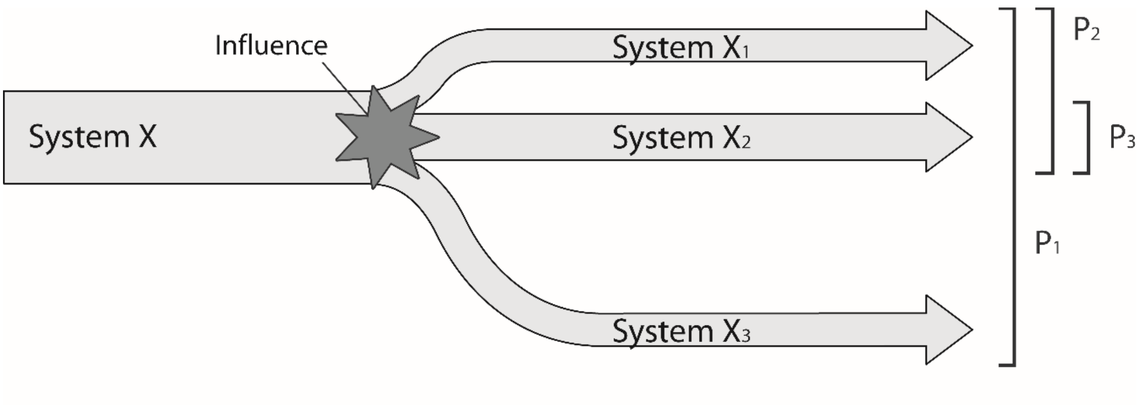


Figure 5-8: Diagram showing Example 5, a system splitting into three groups fulfilling different sets of functions.

> 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 (X_2), some moved to a new area of the island (X_1), and others left to live in a new country (X_3). These groups fulfil different purposes: living as a community (P_1), living as a community anywhere on the island (P_2) and living as a community in the original area of the island (P_3). 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.

5.5 Study 2 summary

RQ3: What can we understand about resilience through communication between stakeholders?

In Study 2, I developed a diagrammatic framework to represent resilience in systems and drew diagrams of examples given by stakeholders in the workshop. This highlighted similarities and differences in what these stakeholders were trying to communicate, which furthered our understanding of the concept of resilience and how to communicate it. The stakeholders discussed resilience using 3 characteristics: resist, recover and change. They related these characteristics to structural and functional aspects of systems.

Resilience is an important concept in the specification, implementation, monitoring and maintenance of many socio-technical 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 resilience experts 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.

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 bearing 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.

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 adopted in this study encourages the definition of a system boundary and purpose, making perspectives on the system explicit. It has been developed from the initial framework presented in Section 5.2 to represent the system function over time as well as the system structure. This framework 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.

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. 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 when a system is affected by influences it can behave in unexpected ways. To compound this, understanding the perspectives of other stakeholders is not trivial.

This study has answered RQ3:

What can we understand about resilience through communication between stakeholders?

Observing stakeholders communicating about resilience meant that we could identify both what they were talking about (i.e. the characteristics of resilience) and how (i.e. what other stakeholders needed to know about their system to understand what they were saying about the resilience of that system). This was helped by the fact that the stakeholders in the workshop were experts in their system of interest and had already thought about resilience in their work. In addition to this, the study showed that an example can be given in conversation of a system exhibiting resilience that everyone in the room understands. However, once I went away and tried to model these examples using a diagrammatic framework, I realised that many of them gave an incomplete picture of what was happening to the system. For example, in most cases when a system changed, the influence on the system was described but it was not specified what enabled this change (the change agent). This means that to understand resilience from talking to system stakeholders, there needs to be a structured approach to this communication, so it is clear what type of resilience each stakeholder is talking about and what in the system they are referring to.

In the next study, I have addressed these challenges by looking at multiple stakeholders perspectives across a single socio-technical system. The findings from this study are used to frame these perspectives, enabling me to identify and compare resilience characteristics across different types of system and levels of abstraction.

6 Understanding resilience through multiple stakeholder perspectives

Talking to stakeholders in the previous two studies has revealed insights about the nature of resilience and how to structure a conversation about socio-technical systems. However, the studies up to this point have been with stakeholders of diverse systems. It has become apparent that stakeholders interpret and discuss systems based on their individual perspective. This means that to build up a full understanding of resilience in a system it is necessary to talk to more than one stakeholder of that system. Therefore, the following study explores how talking to groups of stakeholders about the same system adds to our understanding of resilience in socio-technical systems. This study was preceded with a pilot workshop, detailed in Section 6.1, before a full scale study was conducted, detailed in the remaining sections of this chapter.

This study addresses RQ4:

> *What can we understand about resilience from multiple stakeholder perspectives?*

6.1 Pilot study

In preparation for the third study, I ran a pilot workshop at a conference called 'Resilient Communities?', which was organised by independent think tank The Schumacher Institute and Avon Fire and Rescue Service. There were two objectives for the pilot study: (1) to establish if drawing system maps stimulated conversations between stakeholders about resilience that might not otherwise happen and (2) to inform the design of the main study in terms of structure and content.

There were eight workshop participants who worked in three groups over a period of 45 minutes. To start the workshop I presented three characteristics of resilience, then introduced the ideas of defining a system boundary, defining the system purpose and considering stakeholder perspectives. To aid this, I described an example from Study 2 (Chapter 5). The groups were then given a task to apply this theory to their own systems. Once the participants' had structured their systems, the final task challenged them to consider how their systems might exhibit each characteristic of resilience. At the end of the workshop, participants were asked to fill out a feedback form, reflecting on the tasks.

The workshop tasks were carried out by drawing or writing on two A3 sheets. Sheet 1 (Figure 6-1) had a blank system structure on, with a main system, sub-systems and super-systems. Sheet 2 (Figure 6-2) showed function arrows with space to label the purposes of the system from different perspectives. Each task is discussed in more detail below.

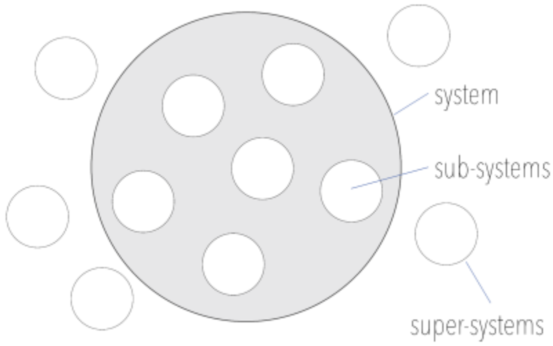


Figure 6-1: Sheet 1 from the workshop showing a system, sub-systems and super-systems. The participants were given an unlabelled version but the labels were shown on a screen as part of the presentation to make sure they understood the diagram.

Figure 6-2: Diagram from Sheet 2 showing the system functioning over time, delivering one of three purposes. The diagram is unlabelled on Sheet 2, with the same set of arrows given for a social sub-system and a technical sub-system.

6.1.1 Task 1: defining a system boundary

The first task in the workshop was for one participant in each group to choose a system that they were a stakeholder of, to use in the workshop exercises. The system was required to be socio-technical. The groups defined the boundary of the system and labelled it on Sheet 1 (see Figure 6-1). The systems that were defined in the workshop by the three groups were:

- Group 1: Surrey Local Resilience Forum
- Group 2: The Railway
- Group 3: Swindon Town

At this point the participants were asked to take on roles within their group, one person (who suggested the system in question) was the system owner, one acted as the social system stakeholder and the other acted as the technical stakeholder. The conference was for stakeholders interested in building resilient communities, so the participants were mainly interested in the social aspects of these systems. In the discussions that took place, the participants did not appear to take on the assigned roles of system owner, social stakeholder and technical stakeholder, but preferred to talk about the system from their own point of view throughout the workshop.

6.1.2 Task 2: defining a system purpose

The second task in the workshop was to define a purpose for the system chosen in Task 1. The participants were asked to label this purpose on an arrow on Sheet 2 (see Figure 6-2). Group 1 defined the purpose of the Surrey Local Resilience Forum as to 'develop community resilient people'. The other groups were less specific. Group 2 listed a set of purposes including the 'low carbon movement of people and goods' as well as 'economic growth and social cohesion'. Group 3 took a broader approach in defining the purpose of Swindon Town, identifying 'fulfilment, vibrancy, functioning' as the main purpose of the system.

Defining the system boundary and the system purpose are not necessarily chronological activities, so the participants were then asked to go back to Sheet 1 and label the sub- and super-systems needed to fulfil the defined purpose. The participants were encouraged to include at least two social and two technical sub-systems. There were a good range of abstraction levels identified, from 'climate change' (Group 3) down to 'ticketing systems' (Group 2). Also, the sub-systems for all groups did include social and technical elements, however, in some cases these were not distinct, for example, 'health' (Group 3) or 'utilities' (Group 1).

6.1.3 Task 3: accounting for stakeholder perspectives

The third task was to revisit group definitions of the system purpose. On Sheet 2, there were three purpose arrows for the main system (Figure 6-2), as well as two more sets of arrows to define the purposes of a social and a technical sub-system. This task was intended to highlight the differences in perspective between stakeholders and encourage each of the participants in the groups to offer an alternative opinion on how the purpose of the system could be defined. The groups generated distinct purposes for the three system perspectives (system, social sub-system, technical sub-system), but having multiple possible purposes for each system seemed to confuse the participants.

6.1.4 Task 4: responding to influences

The fourth task was designed to bring together the characteristics of resilience with the discussions about the participants' systems that took place in Tasks 1-3. The groups were taken through a series of three influences (see Figure 6-3) and asked to discuss how their systems might respond. The aim of this was to establish an understanding of the resilience of their systems.

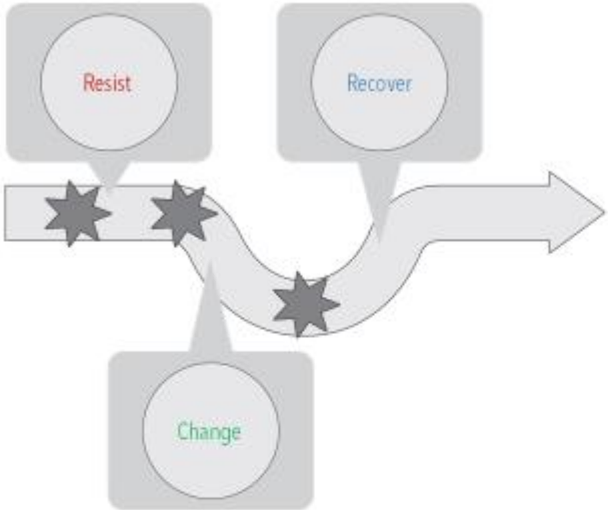


Figure 6-3: Diagram showing a system affected by, and responding to, three influences, which represent the three characteristics of resilience.

The first influence in Figure 6-3 is resisted by the system (exhibiting the first characteristic of resilience), so the participants identified a sub-system on Sheet 1 that they did not want to change, circling it in red pen. We then moved on to the second influence, and the groups were asked to draw a red cross through the system they had identified as resisting influences, because these types of systems are often fragile. Now that one of their defined sub-systems was not operational, the groups were asked to think of how the system could change in response to the second influence (the third characteristic of resilience). There were two aspects to this discussion about system change: what the new purpose of the system was (consulting the purposes defined on Sheet 2), and what in the system enabled it to change (circling relevant sub- and super- systems on Sheet 1 in green pen). The third influence started a recovery process where the system returns to the original purpose. The participants discussed what would be needed to achieve this, annotating the system diagram on Sheet 1 with blue pen.

6.1.5 Learning from the pilot study

I assessed the first objective of the workshop, to establish if the workshop stimulated conversations between stakeholders about resilience that might not otherwise happen, by observing and taking part in the group discussions and by asking for written feedback from the participants. At the start of the workshop, it was apparent that some participants were not used to thinking of their work in terms of systems. Once they had grasped this idea, they began to talk about aspects of their systems they had not previously thought about, such as: how technical sub-systems might interact with social sub-systems; how other stakeholders might not agree with their definition of purpose; how a resilient system might change to fulfil a new purpose; and how distributed control might make their system more able to change.

The written feedback suggested that the main value of the workshop for the participants was in thinking about the structure of their systems, and how the architecture and purpose of the system might change over time. However, some of the participants found the approach 'too academic', making it difficult to grasp the concepts behind the framework in the short space of time. In line with the second workshop objective, I identified a number of observations and improvements, listed in Table 6-1, which were used to inform the main study in this chapter (Section 6.2 onwards).

Table 6-1: Observations from the pilot workshop with resulting improvements that were carried forward to the main study.

	WORKSHOP OBSERVATIONS	RESULTING IMPROVEMENTS
PARTICIPANT AND GROUP STRUCTURE	The workshop participants were mainly interested in the social aspects of their systems, which meant the technical sub-systems were not considered in much detail. This also limited the value of Task 3, exploring the system purpose from different perspectives.	Ensure that study samples have an even balance of technical and social stakeholders.
	Only one group had two stakeholders who were interested in the same system. This appeared to limit the participation of some people who were not familiar with the system being used in the group exercise.	Hold future studies with stakeholders of the same system. This approach should also provide more data about how stakeholders working at different levels of abstraction perceive resilience.

	Although there were benefits to presenting the workshop tasks one by one, once the participants began a task it was difficult to interrupt the ensuing discussions, breaking the groups' flow, and introduce the next task.	Avoid introducing theory at each stage to break up tasks. Instead, design tasks that do not require the stakeholders to have prior theoretical knowledge. One-to-one interviews will also allow the researcher more control over the discussion.
	During each workshop task I went around to each group to discuss their thought processes and listen to their conversations. These discussions were very informative, with explanations of what the participants were drawing and why.	Audio recordings should be used to capture the discussions alongside the system maps.

WORKSHOP CONTENT AND MATERIALS	The sub-systems defined on Sheet 1 mostly were both social and technical. These broad definitions also made it difficult to establish which aspects of the sub-systems the participants were interested in.	Give instructions about how to define these sub-systems as either social or technical. A clear distinction will be easier to arrive at in one-to-one interviews.
	The participants were happy writing on the sheets provided but were reluctant to write over and cross out existing work, or to draw additional lines and system features.	Use a less permanent form for materials, such as sticky notes.
	Some groups defined a set of purposes that were broad or vague.	Give future participants more direction about what the purpose of the system should and should not include, and how long their definitions should be. Ask probing questions to clarify their defined purposes.
	Some of the participants used acronyms when writing on the workshop sheet, making it harder for other participants and me to understand their systems.	Ask the participants to write full names and specific details about the system, probing any aspects that are not clear.

6.2 Method

Following the pilot study, the main study was designed as a series of in depth interviews with stakeholders of a single system. The system chosen was a £1 billion development in a city, initiated and managed by a leading university. The initiative was designed to provide affordable housing for university staff and post-graduates and provide a place to foster university research. The development had long term goals to enhance the university and city, with the term 'resilience' being used in project reports relating to both technical (buildings) and social (communities) systems. To protect the anonymity of the stakeholders in this study, the exact details of the development, including its location, have been withheld.

The interviews were conducted between March-August 2016. At this point, 75% of the phase one development had been built, although no residents had moved in. Further phases of development were planned to extend the site, with the building stage of the project expected to take 15 years.

6.2.1 Sample

In the study 11 stakeholders were interviewed. They were chosen to span across domains and levels of abstraction as shown in Table 6-2. The stakeholders were identified through a combination of direct contact and chain referral sampling (Biernacki & Waldorf, 1981).

Table 6-2: System stakeholders, their job roles, organisational affiliation, and the system they identified as their main system of interest.

PARTICIPANT ID	JOB ROLE	ORGANISATION	SYSTEM OF INTEREST
S1	Community development officer	Local authority	City
S2	Councillor	Local authority	City
S3	Planning officer	Local authority	City
S4	Academic	University	University
S5	Academic and governor	University	University
S6	Former project director	University (project team)	Development
S7	Acting project director	University (project team)	Development
S8	Construction director	University (project team)	Development
S9	Operations director	University (project team)	Development
S10	Architectural firm director	Consultant architects	Lot A*
S11	Architectural firm director	Consultant architects	Lot B

*The development project was sub-divided into physical lots, with different architectural firms contracted to design each lot.

Figure 6-4 shows the distribution of stakeholders according to their job roles. Each level shown is an organisational group. These organisations overlap, with the dotted lines showing the project boundary. All of the stakeholders interviewed were directly involved in the development. Their systems of interest, listed in Table 6-2, coincided with the interests of the organisations they worked for, as seen in Figure 6-4. The 'project team' is not an independent organisation, it is funded by the university. However the stakeholders working in the project team were hired for this specific development project and so the team is distinguished from the two members of the university involved in university governance and research, S4 and S5. The 'consultancies' in this case are two architectural firms who are working on two independent lots on the development.

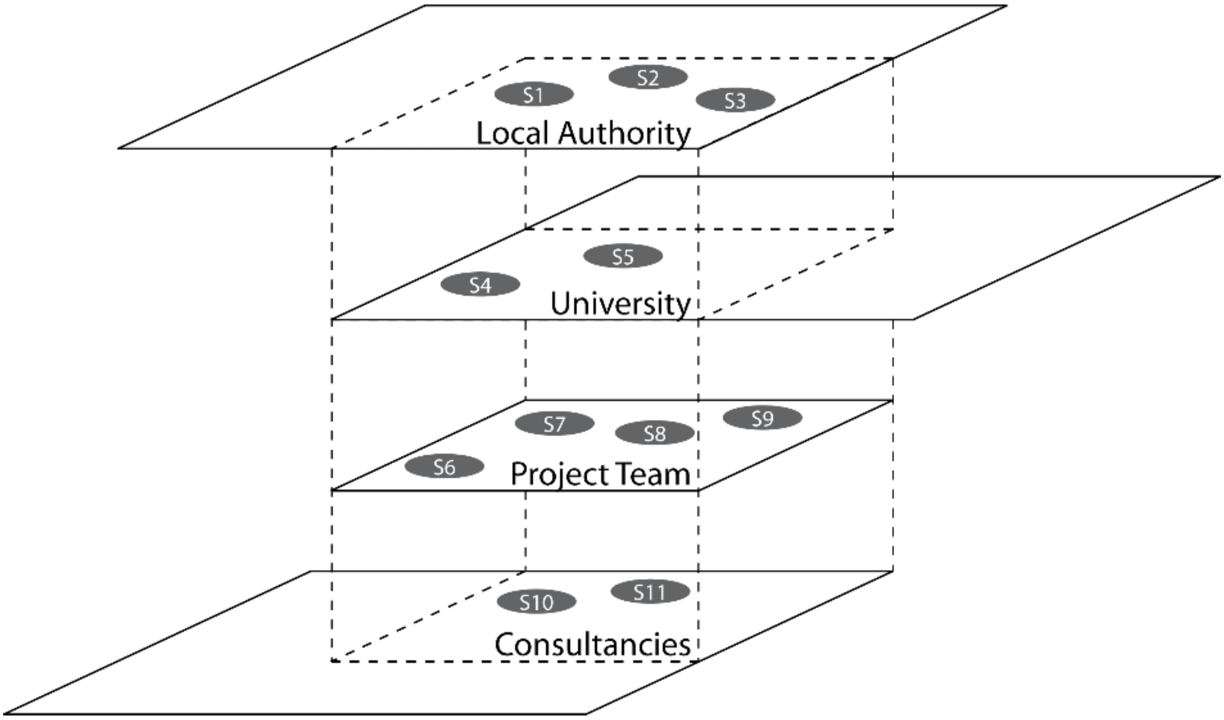


Figure 6-4: Schematic showing the distribution of the stakeholders according to the organisation they worked for. The project team is employed by the university solely to implement the development but is treated as an independent organisation. The local authority, university and consultancies all have parts of the organisation that are not involved with the development project, which are illustrated by the extension of the planes beyond the dotted lines.

6.2.2 Data collection

All interviews were conducted one-to-one at the stakeholders' place of work with the researcher as the interviewer. Each session lasted 53 minutes on average (excluding the introduction and wrap up). With the stakeholders' consent, all interviews were recorded and subsequently converted into a total of over 60,000 words of transcript. A structured interview format was used to ensure all stakeholders were asked the same key questions, although the length of time spent on each question and the number of additional prompt questions varied depending on the stakeholders' answers. This meant that points of interest could be explored in more depth (Patton, 1990).

The interviews had two main parts. In the first part, the stakeholders were asked questions about their job role and how it related to the development project, what resilience meant to them, and ways they might design for resilience. This part of the interview was designed to build rapport and to gauge each stakeholder's initial level of understanding of resilience. After the initial discussion, the interview moved onto the second part, which involved a system mapping exercise.

System mapping exercise

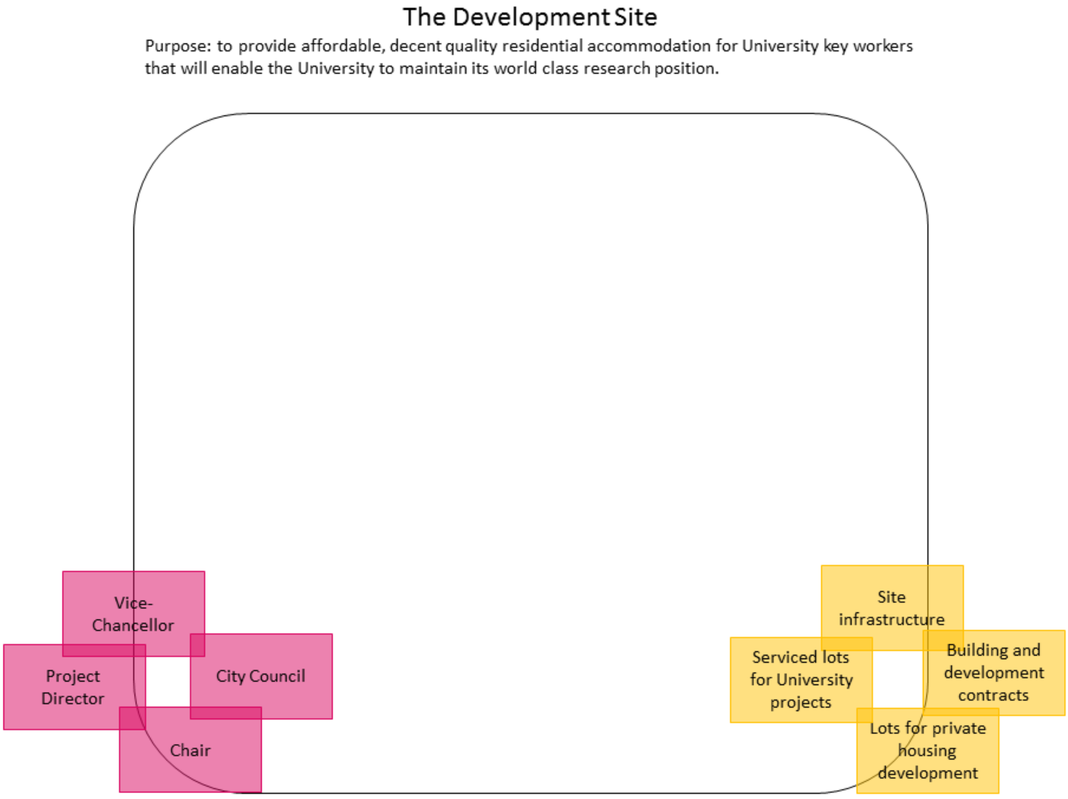
In the system mapping exercise the stakeholders were asked to choose a system boundary that reflected their level of abstraction. For example, a stakeholder involved in running the university might think about the university as their main system, with a new development as one sub-system in the university. Other systems such as the local authority might be thought of as external to that main system. Conversely, a stakeholder involved in managing the city might think about the university as one sub-system of the city. Each system mapping exercise was conducted from the perspective of the individual stakeholder.

The mapping exercise started with a blank sheet of A3 paper. I started by explaining the exercise and drawing a large rectangle as a system boundary. Starting the exercise this way, as opposed to having pre-printed sheets, was intended to make the exercise more approachable and reduce anxiety around visual literacy (Bagnoli, 2009; Crilly et al., 2006). Once this boundary was drawn, the stakeholders were asked to:

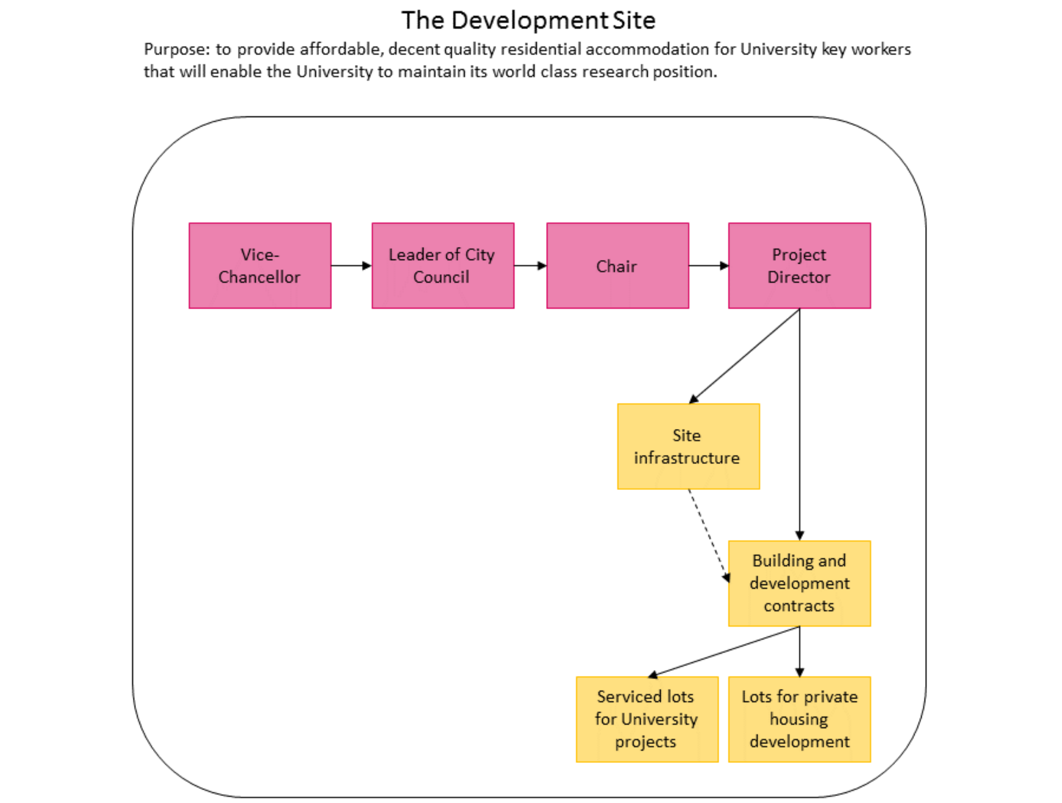
1. Label the system boundary
2. Write a system purpose for the specified boundary at the top of the page
3. Write three social systems on pink sticky notes
4. Write three technical systems on yellow sticky notes
5. Arrange the sticky notes and draw relationships between them
6. Assign coloured dots to each sticky note to represent the three resilience characteristics (resist – red, recover – blue, change – green)
7. Discuss examples relating to resilience and develop the system map with new additions on green sticky notes

The stakeholders were free to draw relationships as they chose, using lines or directional arrows. There were also no constraints on what type of 'thing' the sub-systems had to be. For instance, the stakeholders chose to include physical things like buildings, contractual things like budgets or legal contracts, and abstract things like reputation or performance. Similarly, the 'people' could be individuals, groups or organisations, as defined by the stakeholders.

In the following pages, an example of how a stakeholder's system map was built up is shown in Figure 6-5, and the variety of system maps can be seen across the 11 stakeholders' diagrams in Figure 6-6. In the interviews, social systems on the pink sticky notes were referred to as 'people, who could be individuals or groups of people', and technical systems on the yellow sticky notes were referred to as 'things, which are any sub-systems that are not people'.



(a)

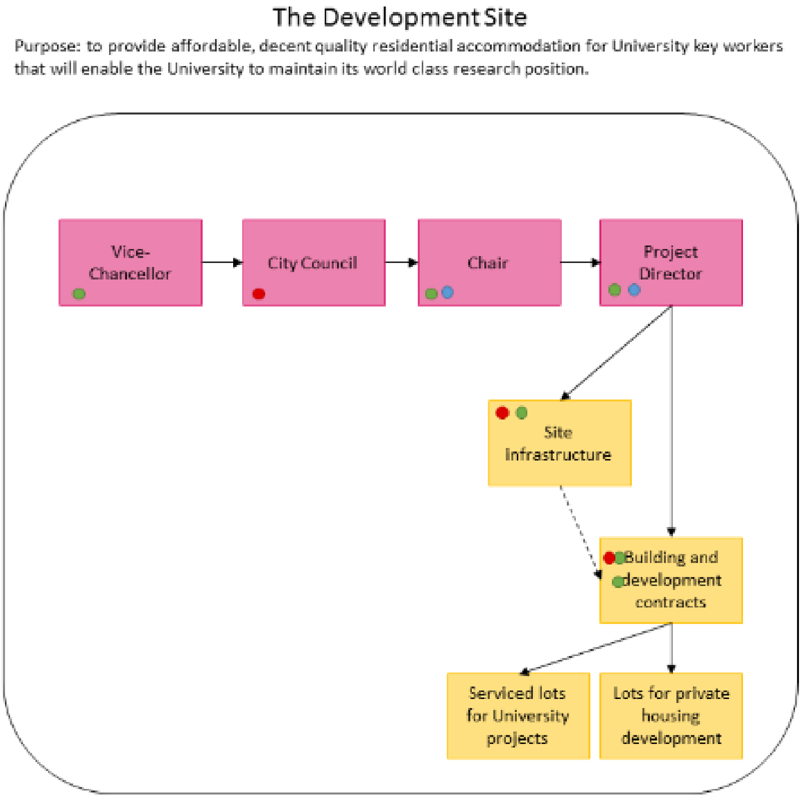


(b)

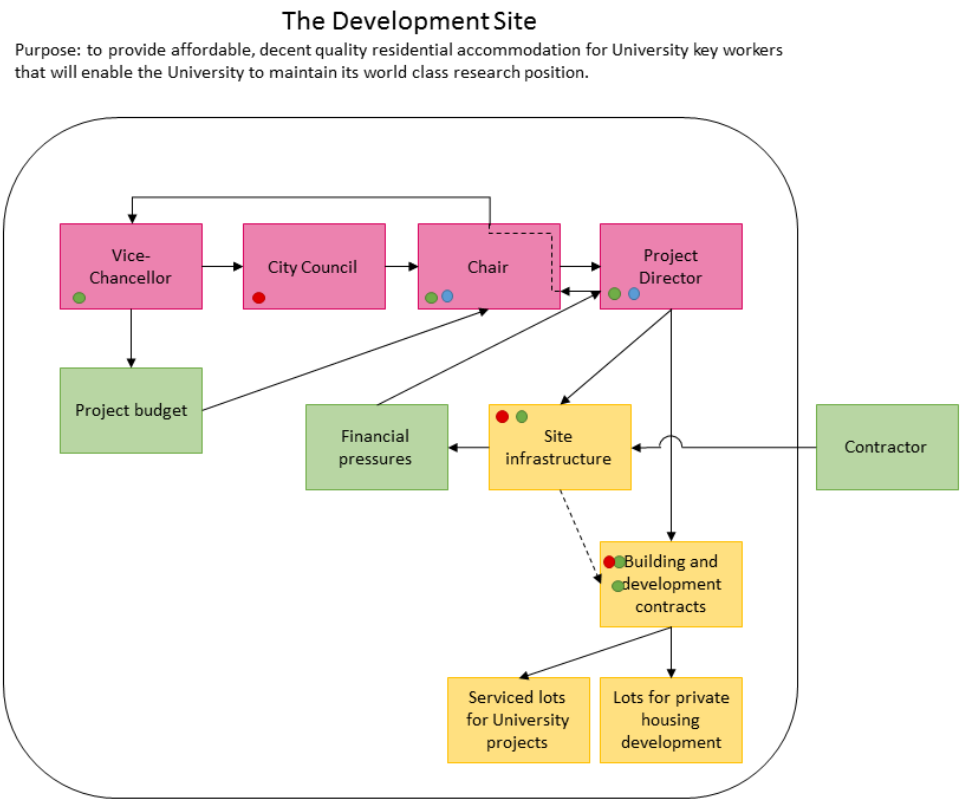
Figure 6-5: Four sequential stages of the system mapping exercise:

a. steps 1-4: defining a system boundary ['The Development Site' in this instance], system purpose, identifying 'people' [pink] and 'things' [yellow] as sub-systems;

b. step 5: arranging sub-systems and drawing relationships;

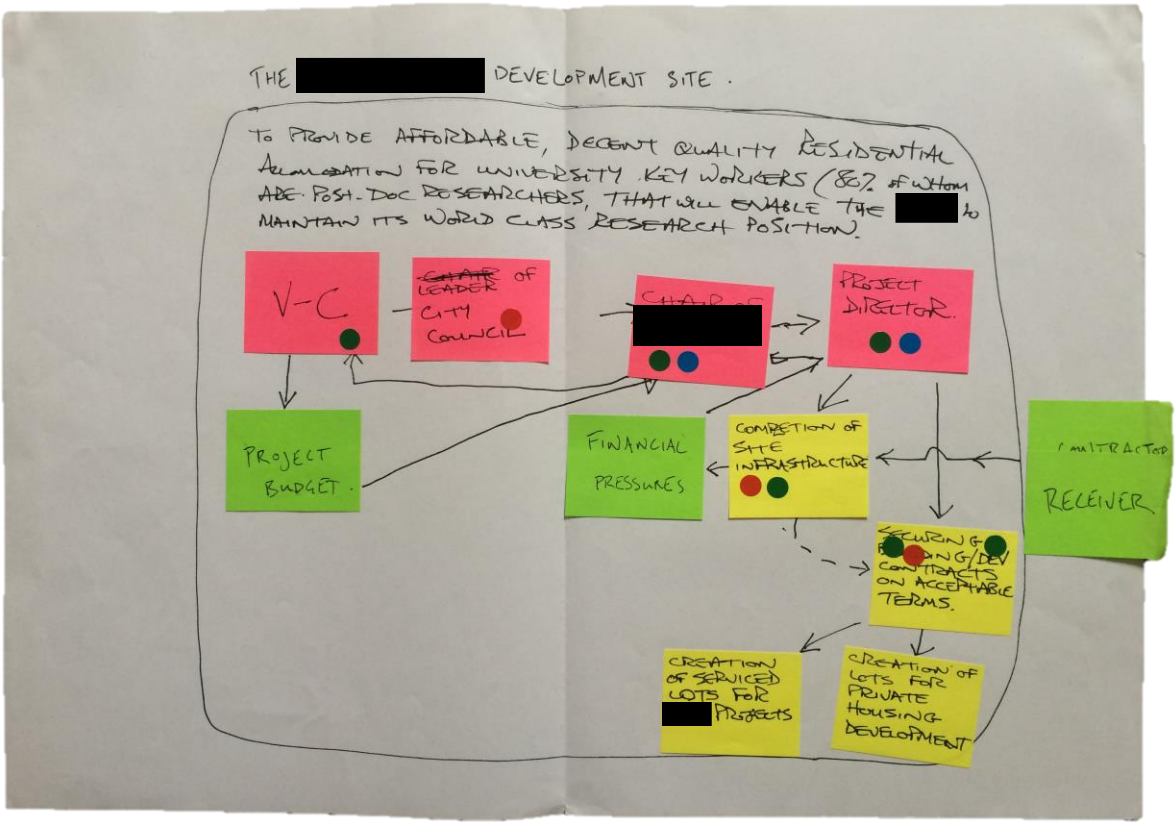


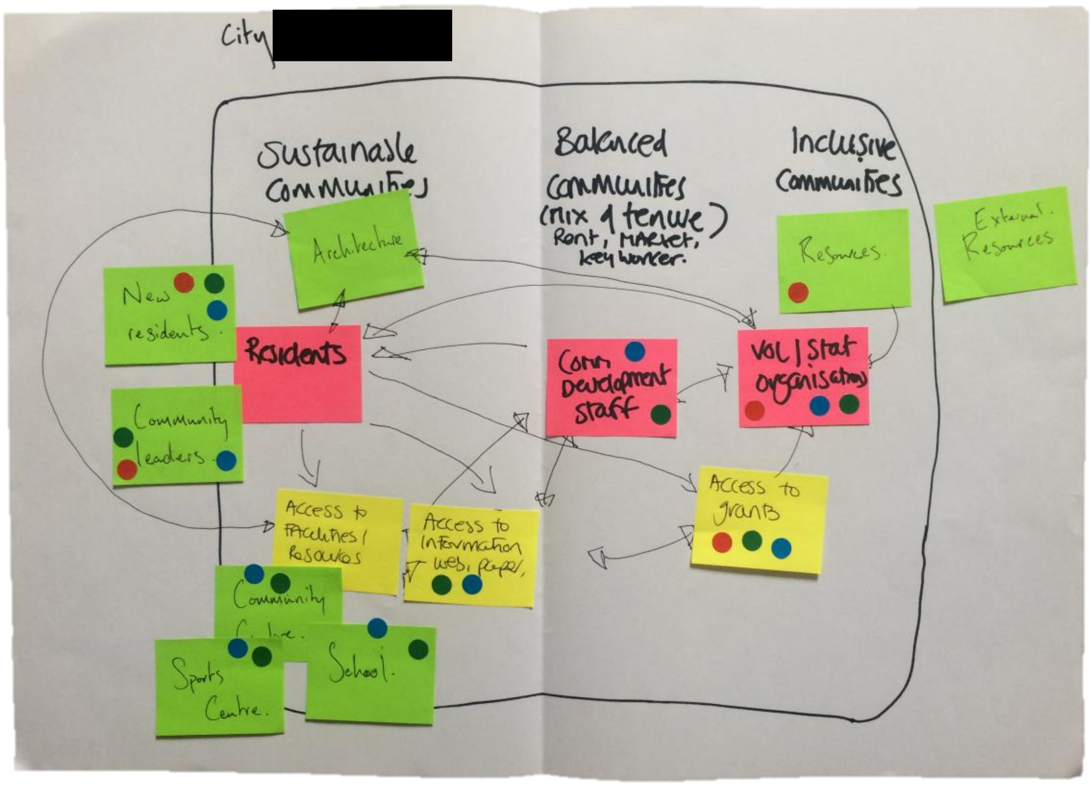
(c)

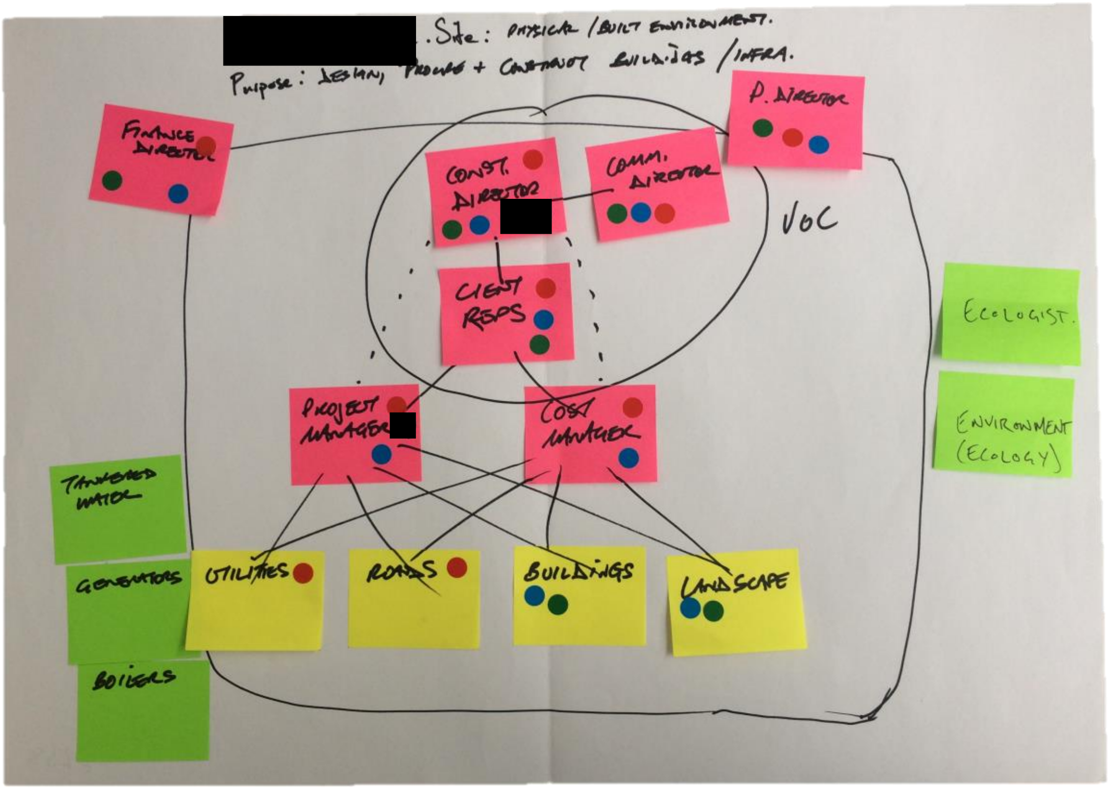


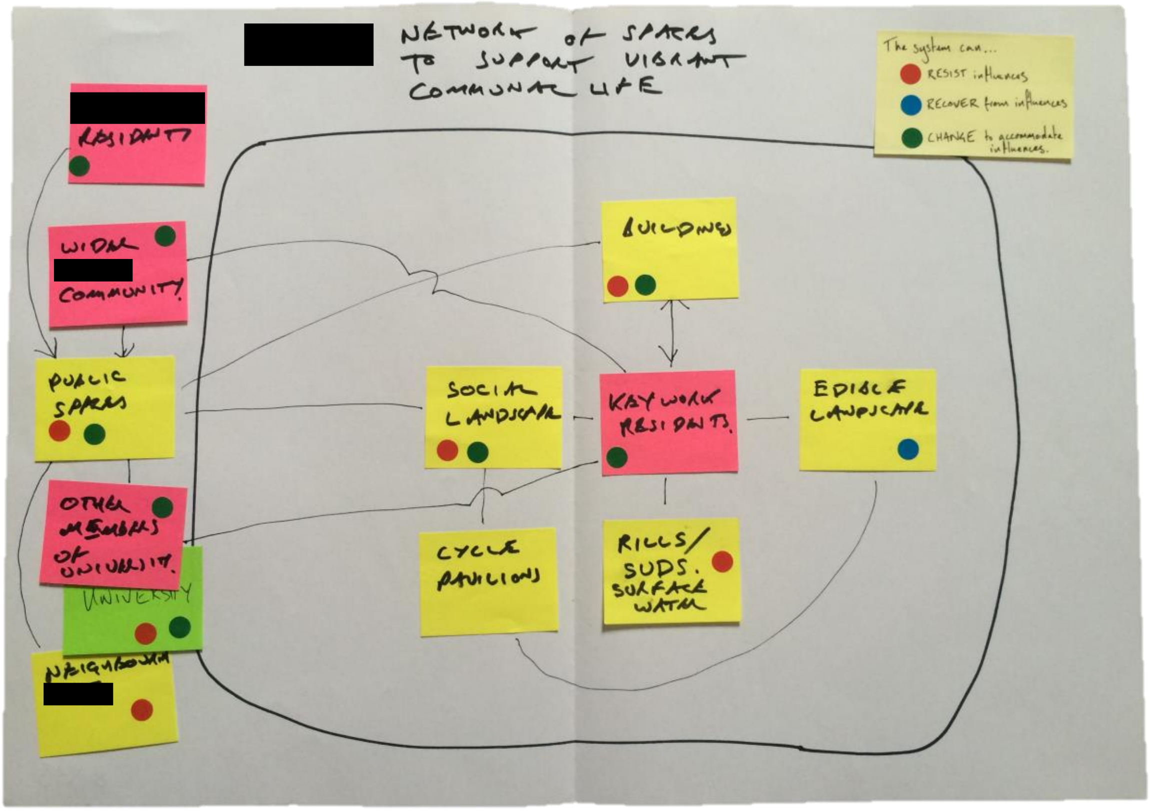
(d)

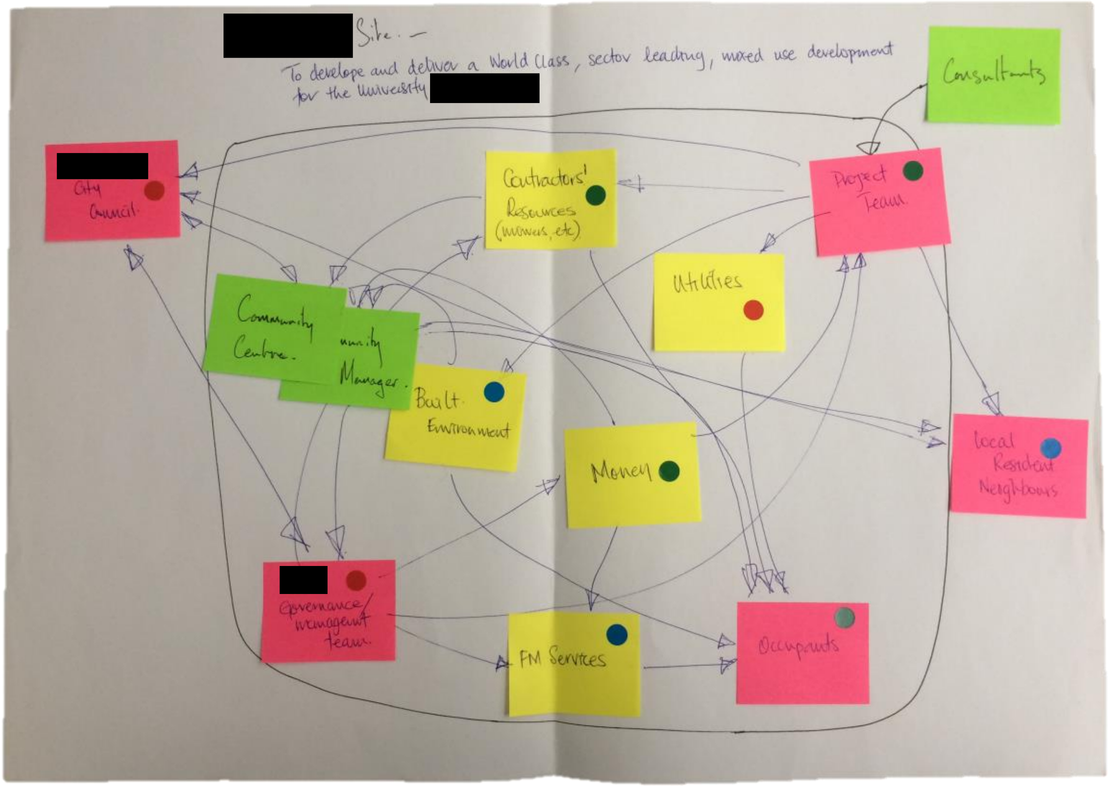
c. step 6: identifying resilience characteristics for each sub-system;
d. step 7: exploring and developing the system map based on further discussion [additions in green].


THE [redacted] DEVELOPMENT SITE.
TO PROVIDE AFFORDABLE, DECENT QUALITY RESIDENTIAL ACCOMMODATION FOR UNIVERSITY KEY WORKERS (80% of whom ARE POST-DOC RESEARCHERS, THAT WILL ENABLE THE [redacted] to MAINTAIN ITS WORLD CLASS RESEARCH POSITION.
V-C
CHAIR LEADER OF CITY COUNCIL
CHAIR OF [redacted]
PROJECT DIRECTOR.
PROJECT BUDGET.
FINANCIAL PRESSURES
COMPLETION OF SITE INFRASTRUCTURE
CONTRACTED RECEIVER
SECURING BUILDING/DEV CONTRACTS ON ACCEPTABLE TERMS.
CREATION OF SERVICED LOTS FOR [redacted] PROJECTS
CREATION OF LOTS FOR PRIVATE HOUSING DEVELOPMENT


City [redacted]
Sustainable Communities
Balanced Communities (mix of tenure) Rent, Market, key worker.
Inclusive Communities
Architecture
New residents.
Residents
Community leaders
Comm Development Staff
Vol/Stat organisations
Resources.
External Resources.
Access to facilities/resources
Access to information web, paper,
Access to grants
Community Centre.
Sports Centre.
School.

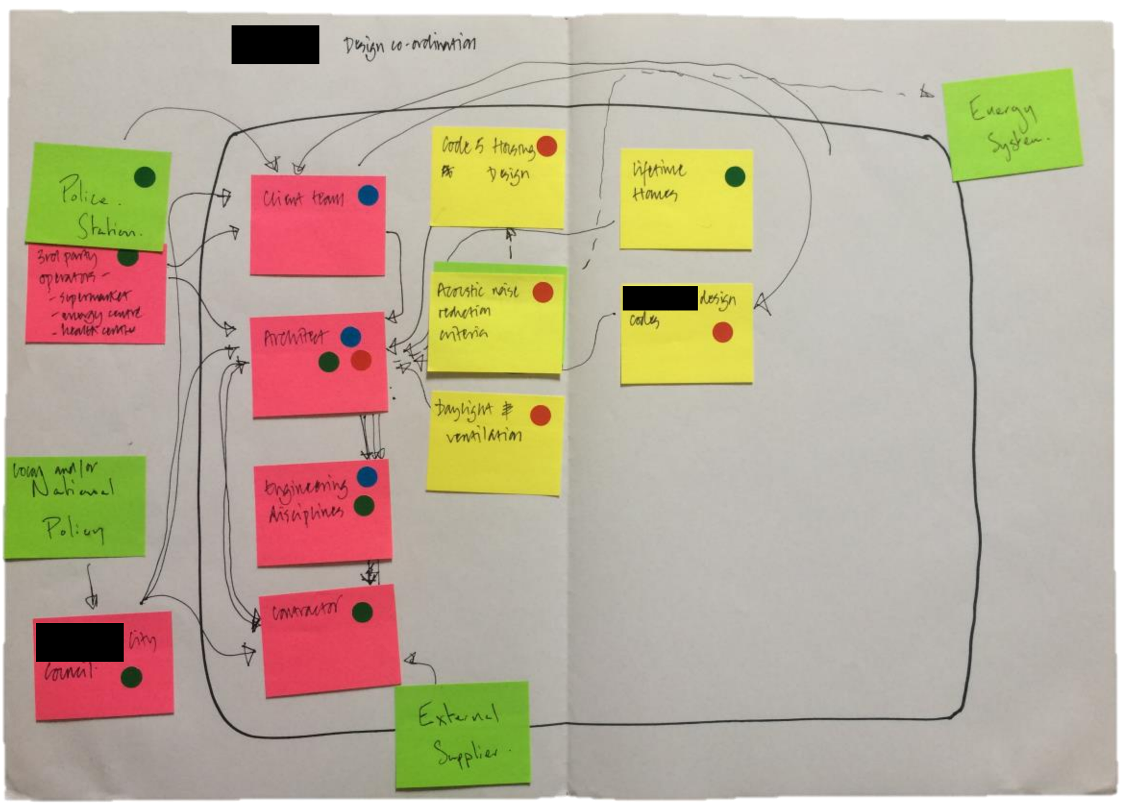

[redacted] Site: physical/built environment.
Purpose: design, procure + construct buildings/infra.
Finance Director
Const. Director [redacted]
Comm. Director
P. Director
VoC
Client Reps
Project Manager [redacted]
Cost Manager
Ecologist.
Environment (Ecology)
Tankered water
Generators
Boilers
Utilities
Roads
Buildings
Landscape


[redacted]
Network of spaces to support vibrant communal life
The system can...
RESIST influences
RECOVER from influences
CHANGE to accommodate influences.
[redacted] Residents
Wider [redacted] Community
Public spaces
Other members of university
University
Neighbourhood [redacted]
Buildings
Social landscape
Key worker residents
Edible landscape
Cycle pavilions
Rills/SUDS. Surface water

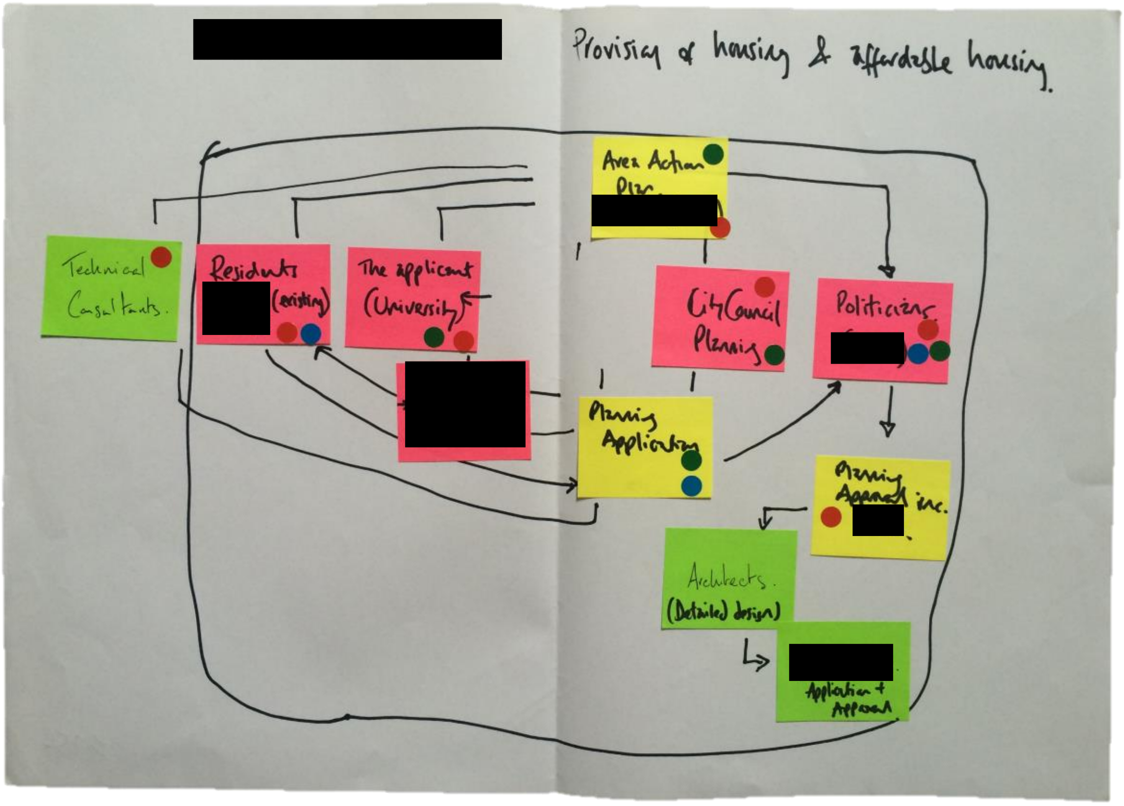

[redacted] Site. –
To develope and deliver a World Class, sector leading, mixed use development for the University [redacted]
Consultants
[redacted]
City Council
Contractors' Resources (workers, etc)
Project Team
Utilities
Community Centre.
Manager.
Built Environment
Money
Local Resident Neighbours
[redacted]
Governance/management team
FM Services
Occupants


City and University. – to find a way to retain a world class academic environment which continues to excel on a global scale.
STUDENTS
REPUTATION & PERFORMANCE
WEST [redacted]
FACULTY
BEAUTIFUL BUILDINGS
ARCHITECTS
ENABLERS UNIV
[redacted]
BUILDINGS
PROJECT TEAM.
ACCESSIBILITY
[redacted]
ACCESS PLAN
ENABLERS CITY

City [redacted] – to retain a small city character with green belt + transport links.
Central Government.
Globalisation
Developers.
Civic
Political
THE MAYOR + COUNCIL
RESIDENTS' ASSOCIATIONS
Population
Local Press
County Council
[redacted] Site.
STREET FURNITURE + SURFACING
MODEST SCALE BUILDINGS
VISIBLE SIGNS OF COMMUNITY
OPEN SPACE
LOW IMPACT PUBLIC TRANSPORT
INDEPENDENT TRADERS
ULTURAL ROVIDERS



[redacted] Design co-ordination
Police Station.
3rd party operators – supermarket – energy centre – health centre
Local and/or National Policy
[redacted] City Council.
Client team
Architect
Engineering disciplines
Contractor
External Suppliers.
Code 5 Housing Design
Acoustic noise reduction criteria
Daylight & ventilation
Lifetime Homes
[redacted] design codes
Energy System.


[redacted]
Provision of housing & affordable housing
Area Action Plan
[redacted]
Technical Consultants
Residents [redacted] (existing)
The applicant (University)
[redacted]
City Council Planning
Politicians [redacted]
Planning Application
Planning Approval inc. [redacted]
Architects (Detailed design)
[redacted] Application + Approval

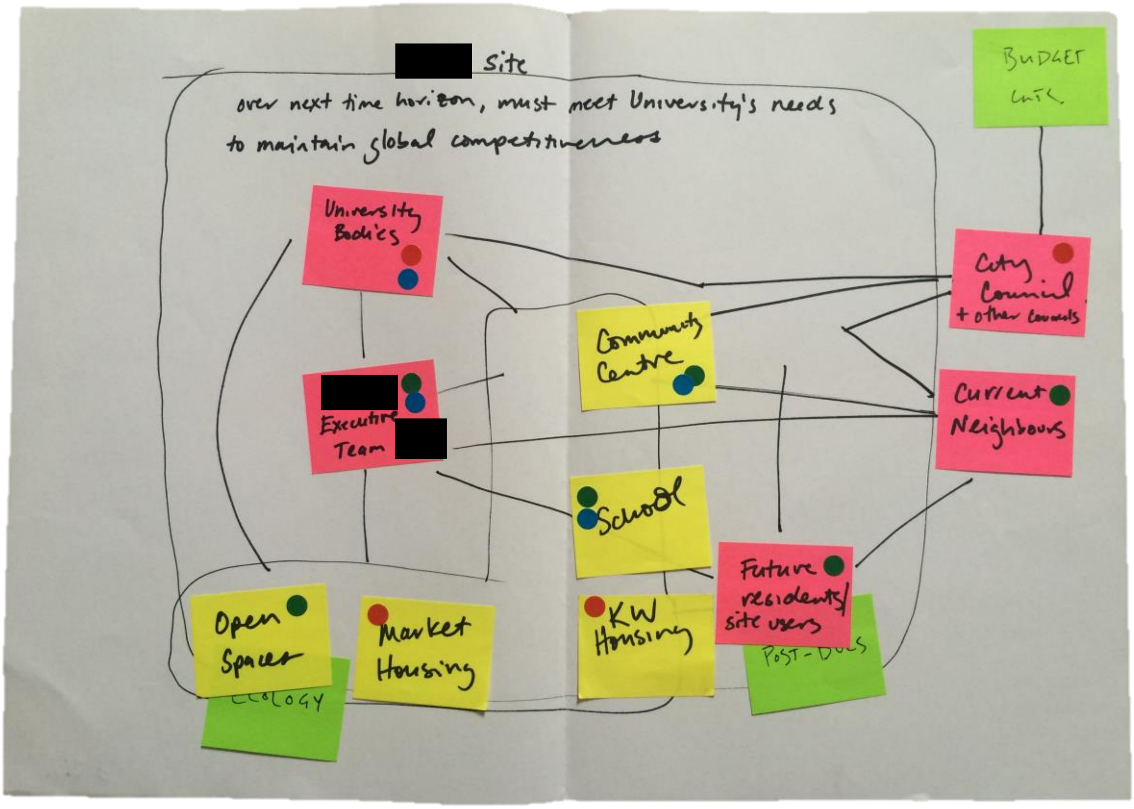

[redacted] site
over next time horizon, must meet University's needs
to maintain global competitiveness
BUDGET
University Bodies
City Council + other councils
Community Centre
[redacted] Executive Team [redacted]
Current Neighbours
School
Future residents/ site users
Open Spaces
ECOLOGY
Market Housing
KW Housing
POST-DOCS

Figure 6-6: The 11 stakeholders' completed system diagrams.

The process of drawing the system map prompted discussion about resilience. The main points of discussion were around the purpose of the system and assigning resilience characteristics. When assigning the three resilience characteristics (resist, recover, change) to the sticky notes, the stakeholders were asked to give examples of how each sub-system exhibited the characteristics chosen. Once the system map was complete, to prompt further discussion, I chose one sub-system with a 'resist' sticker on and removed that sub-system from the map entirely asking, 'what would happen to the main system if this sub-system broke down?' In this way, potential scenarios were explored. During the scenario mapping discussion, I also used green sticky notes to introduce new sub-systems to the map, as seen in Figure 6-5d. Some of the maps in Figure 6-6 include green sticky notes that were used to make connections between different stakeholders' maps. For example, in an interview with stakeholder S1, who was not directly involved with the development buildings, I wrote 'architecture' on a green sticky note and asked the stakeholder to incorporate it into their system map.

6.2.3 Data analysis

The interview transcripts (covering both the initial discussion and system mapping exercise) were qualitatively coded in Atlas.ti using a pre-defined code list, which was developed from a previous research study. Although a code list was used, it was expected that new codes would emerge from the data during an iterative inductive process (Thomas, 2006).

The system maps were converted into a digital format, which showed the sequence of construction (see Figure 6-5). These digital system maps were linked to the transcripts, permitting the researchers to see what the stakeholders' were saying as they produced the original maps. An example of this data capture is shown in Figure 6-7.

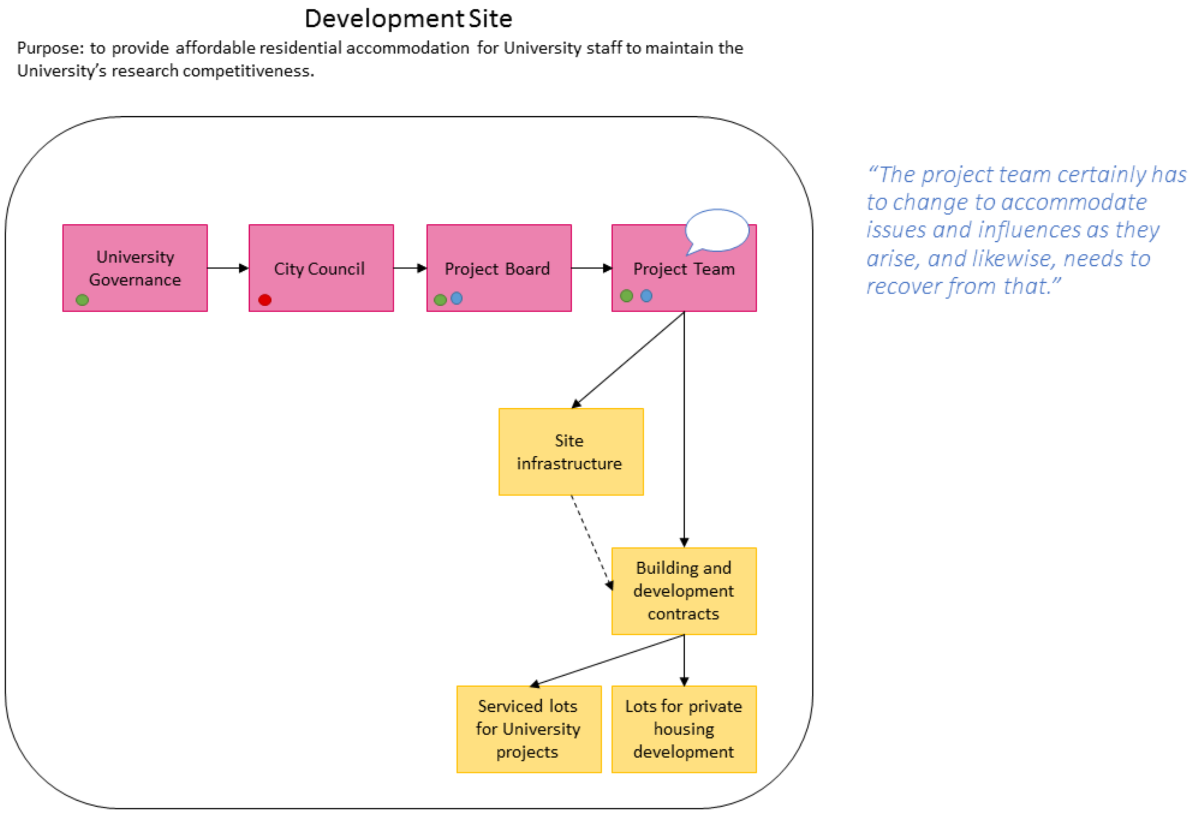


Figure 6-7: Example of a digital system map where the transcript is linked to the map. The text on the right shows what the stakeholder was saying at this point in the system map building exercise. The speech bubble on the pink sticky note points to the accompanying action – the stakeholder sticking green and blue dots onto the 'Project Team' sticky note.

The digital maps were useful in understanding the data and representing it to other researchers. They were combined with annotated print outs of the original maps and used to support the transcript coding.

Support of data analysis

Initially, I coded all of the transcripts and then a second researcher was asked to code five of them (S1, S4, S5, S7 and S10) to explore and incorporate other interpretations. These transcripts were chosen by taking every other interview chronologically, to account for any changes in the interviewing style as I developed an understanding of the development and emerging themes. When selected this way, the interviews also covered all four levels of abstraction (as seen in Table 6-2) and, as judged by the researcher, were a good representation of the breadth of topics discussed in the interviews.

The second researcher was briefed on the research goal of the study, namely, to find out what we can learn about resilience by talking to different stakeholders of the same system. No other details were shared about the coding scheme used by the primary researcher or themes from previous studies. The second researcher was then asked to code the transcripts based on themes that emerged from the data. The results from this validation confirmed that the pre-existing code list was a good match for the data. The only theme that was not addressed by the secondary researcher was that of stakeholder perspectives. This is because this theme emerged from comparisons across transcripts and system maps, rather than from individual transcripts. The emphasis on each theme reflected the emphasis found by the primary coder.

The findings from this study are discussed in three parts. The first part (6.3.1) compares and contrasts stakeholder perspectives against three system dimensions: system boundary, system purpose, and system timescale. The second part (6.3.2) brings together these diverse perspectives and points to what we can learn about resilience looking across timescales, interfaces, change mechanisms, resilience characteristics, and system types. The third part (6.3.3) reflects on the method used in this study, with a focus on the system mapping exercise. Each of these parts will be discussed in turn supported by quotes from the data. In some cases these quotes have been edited for clarity or to protect the anonymity of stakeholders.

6.3 Findings on system dimensions

The study was deliberately designed to gather a range of stakeholder perspectives across domain boundaries and levels of abstraction. The level of abstraction of each stakeholder was indeed an important factor in how each stakeholder viewed resilience, represented by how they identified *system boundary and purpose*. The second main factor that influenced the stakeholders' perspectives was *system timescale*. This was not predefined by the system mapping exercise but it varied between stakeholders and had a large impact on how they discussed resilience.

6.3.1 System boundary and purpose

In the system mapping exercise, the stakeholders first defined a system boundary, which was their main system of interest, and then defined a purpose for that boundary. Four systems were identified: the city, the university, the development site, and an individual lot on the development. The purposes that the stakeholders assigned to these systems can be seen in Table 6-3.

Table 6-3: System purposes as defined by the stakeholders.

PARTICIPANT ID	SYSTEM BOUNDARY	PURPOSE
S1	City	To provide sustainable, balanced, inclusive communities.
S2	City	To retain the city's character with a green belt and transport links.
S3	City	To provide affordable housing.
S4	University	To retain a world-class academic environment which continues to excel on a global scale.
S5	University	To maintain research outputs of ideas and people.
S6	Development	To provide affordable, quality accommodation for university staff, which will enable the university to maintain its world-class status.
S7	Development	To maintain university's global competitiveness over the next time horizon.
S8	Development	To design, procure and construct buildings and infrastructure.
S9	Development	To develop and deliver a world class, sector leading, mixed use development for the university.
S10	Lot	To provide design coordination.
S11	Lot	To provide a network of spaces to support communal life.

The list of purposes in Table 6-3 show that the stakeholder's definition of purpose is dependent on their system of interest and their perspective on that system. The two stakeholders leading the project team (S6 and S7), who both defined the development site as their system boundary, defined the purpose of the site in the context of the university's overall goal, i.e. maintaining competitiveness. Conversely, those in more specialised roles considered the development at a different level of abstraction. For example, the construction director (S8) also defined the development site as their system boundary but identified the purpose of the system as the production of buildings and infrastructure. In practice, these boundaries and purposes were framed by the job role of the stakeholders and the people and things they interact with on a day-to-day basis:

> *'I'm responsible for the design, procurement and construction. [...] I interact very closely with the rest of the project team and I have to make sure that they can operate effectively in the same sphere but they're not involved day-to-day in terms of design, procurement and construction of the buildings.' – S8*

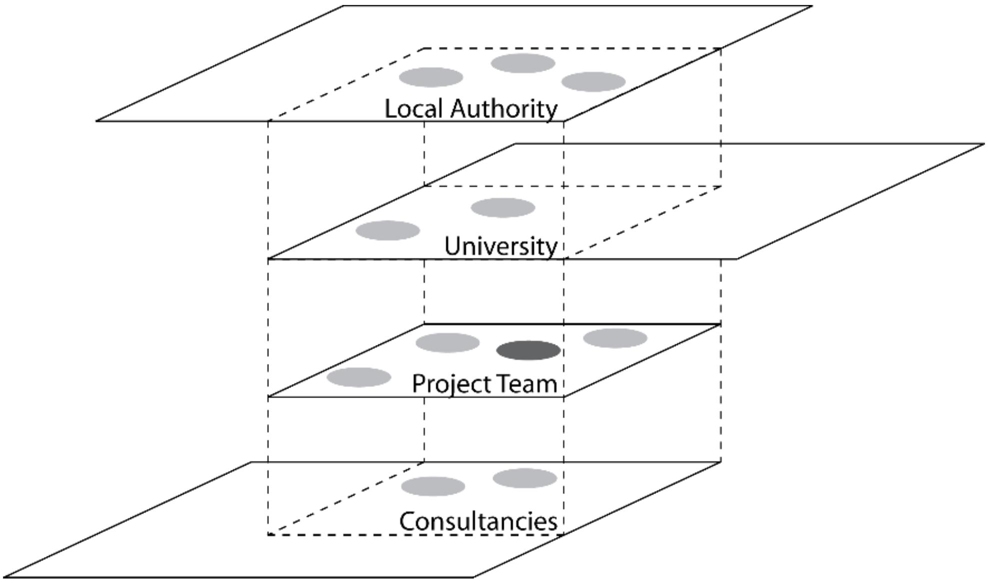


Figure 6-8: Stakeholder S8's position in the system (darker dot) relative to the other stakeholders.

These differences in stakeholder purposes may seem trivial, however these boundaries and purposes determine what the stakeholders identified as most important in the system. For example, when constructing the system map, stakeholder S6 chose social systems involved in governance (e.g. university governance, local authority, and project team), whereas stakeholder S8 chose social systems from a project team level down to managers of utilities, roads and buildings. Defining a system boundary and defining a system purpose are both important because the former broadly frames the problem and the latter points to the types of social and technical sub-systems a stakeholder considers from their perspective. It is only by making these factors explicit that we can understand how stakeholders view resilience. This can be seen in the discussion with stakeholder S5, who defined their system's purpose as maintaining the university's research outputs. When asked to relate this purpose to resilience they said:

> *'Whatever kind of institution we are in 50 years, the development will add to the strength of the University because [the development is] a fantastic resource. Either for places to live, for places to work or as a source of income. It really doesn't matter. In any of those modes, it's making the University more resilient.' – S5*

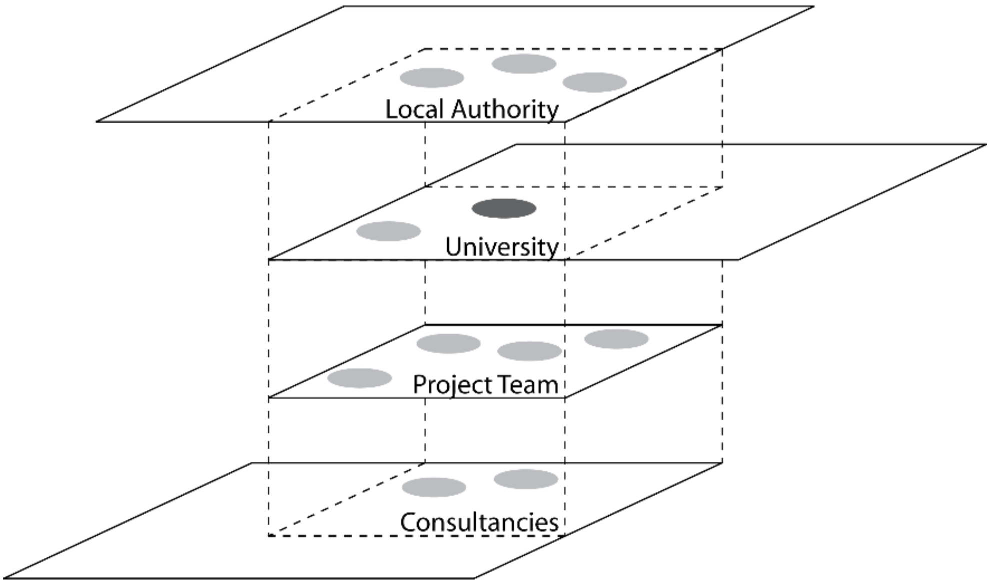


Figure 6-9: Stakeholder S5's position in the system (darker dot) relative to the other stakeholders.

This contrasts with the project teams' goal of providing affordable accommodation, and there are implications for the design of the buildings on the development. For the project director cost is a major driver whereas for the stakeholders operating at the university level (S4 and S5), the legacy of the buildings was deemed more important than its initial function. One stakeholder described this by comparing the new development buildings to an old university building in the city that was still in use:

> *'For an older building, although you might gut the inside, the essential features that make it beautiful are not changed. The [old university building] is a good example. It's a beautiful, beautiful building from the outside and it has been mucked about on the inside to make it functional, but its real resilience is that they haven't been allowed to rip it apart. In the*

development the buildings that are being designed are quite flexible, but they will be unable to retain their essential character when they're subject to change.' – S4

This idea of retaining an 'essential character' was reiterated by other stakeholders. For example, stakeholder S2, who was most interested in the resilience of the city, said:

'I think that cities are rather like human beings, they have intrinsic value and intrinsic worth. They don't have to be justified by what they do or what they aim to do.' – S2

For complex systems, such as universities and cities, purpose is something that is subjective and multifaceted. When a stakeholder has a clear goal or contract, a system's purpose can be defined in terms of technical systems or outcomes. For example, the project team were ultimately responsible for delivering a technical system (the development buildings and infrastructure) following a plan and budget. However, many of the stakeholders were trying to articulate a purpose that was a combination of social and technical systems, with goals that are hard to measure. One architect described this in terms of selling a dream:

'So part of what we do is comply with these technical requirements, but also we sell dreams.' – S10

This balance between higher level 'dreams' and the delivery of technical systems means that many stakeholders described themselves as thinking at different levels of abstraction within (and beyond) the system boundary they defined. The architect quoted above described this process:

'It's going from the micro to the macro. So at one level you're working at town planning level and then you zoom in a little bit more and you're looking at how you mitigate the impact of lorry deliveries. So that's what we do, constantly moving between the two scales, so you have to have a bit of an idea about where you're heading to, and the detail to inform the more fluid fluffy things.' – S10

Another stakeholder described how they had chosen a certain 'lens' to draw their system map but they could have chosen another, which would mean discussing the system at a different level of abstraction. This means that even a single stakeholder can be concerned with multiple system boundaries. By definition, the boundary that they choose will influence their definition of purpose. Whilst these multiple lenses might encapsulate different levels of abstraction, from overall vision to implementation details, there can also be multiple lenses that represent a system, or a stakeholder, at different points in time.

6.3.2 System timescale

System timeframe was a major factor that influenced stakeholders' perspectives. Each stakeholder thought about the development relative to a timescale which was largely defined by their job role but also was affected by other parameters that were harder to define including personal values and domain outlook. For example, one stakeholder's job required them to be involved for a short period of time in the planning of a development, but as part of that planning role, they had to think ahead to how the finished development would operate. In addition, they also lived in the city so were concerned about the impact of the development on that city in the long term. This stakeholders' perspective on timescale covered an extended period, although the stance they took on the system at any one time could be with respect to either the development as a plan or the development as a place. In this way, all of the stakeholders' perspectives on system timescale were layered and multi-faceted. The relationship between time and perspective was also interdependent; the timescale the stakeholders thought about affected their perspective, and the stakeholders' perspectives affected the timescale they thought about.

In the system mapping exercise, the stakeholders' were required to define a system boundary and purpose, which delimited the timescale that was discussed. For example, both architects defined their system boundary as a lot on the development. One of these architects, S10, defined their purpose in terms of 'design coordination', which is the purpose of the architectural firm itself. This meant that the people and things identified in the system map were related to the development as a design and implementation project (e.g. contractors, acoustic noise criteria and design codes). However, the other architect, S11, framed the discussion around the development as a place, which was the product of their design process. This stakeholder defined the system purpose as 'To provide a network of spaces to support communal life.' Correspondingly the systems identified in the system map were related to the development as a living environment (e.g. residents, buildings and public spaces). Defining the system purpose in this way was useful because the conversation moved from a general discussion across a breadth of timescales at the start of the interview to a focused, well-defined discussion in the mapping exercise.

Looking across all of the stakeholders' data, there appeared to be three distinct time periods, or epochs (Ross & Rhodes, 2008), which are detailed in Table 6-4.

Table 6-4: Details about the three time periods of the development: plan, process and product.

EPOCH	DESCRIPTION	TIME	SOCIAL SYSTEM EXAMPLES	TECHNICAL SYSTEM EXAMPLES
Plan	Development plans drawn up	10 years	University; city council; city residents	Planning application; planning approval; plan
Process	Development built out	15 years	University; project team; architects	Buildings; infrastructure; utilities
Product	Development in use	60 years	University; city council; development residents	Building; landscape; services for residents

The stakeholders have been mapped to these three epochs in Figure 6-10 according to what was discussed in each interview. The horizontal bars represent each stakeholder, with the darker sections indicating the timeframe that was primarily referred to in the system mapping exercise, and the lighter sections showing other epochs that were covered by each stakeholder. The dotted vertical line shows the point in time when the interviews were conducted (early 2016). As might be expected, all of the stakeholders at some point talked about their system of interest as a 'product'. This is because 'plans' and 'processes' are forward looking, with the 'product' as the end goal.

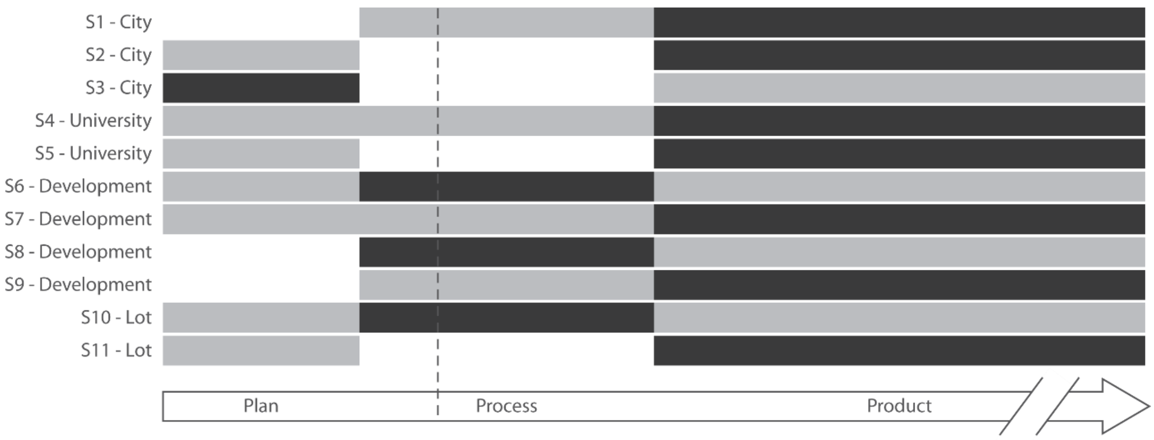


Figure 6-10: System timeline divided into three epochs: plan, process, and product. Stakeholders are mapped onto the timeline with horizontal bars representing the epochs that were discussed in each interview. The darker bars show the epochs that each stakeholder focused on in the system mapping exercise.

All of the stakeholders were interviewed in the fourth year of the 'process' stage of the development. This means that the 'plan' timescale is based on what has already happened, whilst the 'process' timescale is based on current project plans, and the 'product' timescale is based on design practice (e.g. the architects said that they generally design buildings to last for 60 years). There were a few discrepancies for the 'product' length of time, with some stakeholders saying they thought about what the development would be like in 100-250 years' time. However, an outlook of 60 years is generally representative of examples given in the interviews of the development in use.

Making distinctions between time periods is useful because they represent a marked change in the way stakeholders talked about resilience. For example, the stakeholders who span across all three epochs in Figure 6-10 (S4, S6, S7 and S10) were all senior stakeholders who were managing their respective systems. These stakeholder's job roles required them to take a long term, high-level view. This contrasted with stakeholders who had very specific job roles and tended to focus on one epoch (e.g. S2 and S3).

6.4 Findings on resilience across multiple perspectives

Once the stakeholders' perspectives were understood, the data could be analysed to reveal insights into the nature of resilience in the context of socio-technical systems.

6.4.1 Timescales

It is important to note that time has an effect that is independent of any one perspective. Systems change over time, both in their composition and in the way they respond to influences. This means that the structures and functions that allow a system to be resilient at one point in time, might be different at another point in time. For example, one stakeholder, S7, after describing how they thought the resilience for the development came from the university, realised that this might change in the future once the development was in use:

> *'The resilience of this project comes from the university. As a place, when the development is built and operating as part of the community, I suppose the resilience will then come from the residents, and some of the organisations that are working on the ground, like the school and the community centre.' – S7*

Although, as one stakeholder pointed out, having a social system present across multiple epochs, as a consistent stakeholder, can increase the resilience of a system:

> *'I actually think most of the resilience for the development comes from the university's backing and commitment to being the long term stakeholder, that's what sets it apart from*

> *other developments. I think you might find that other housing developments are much more fragile.' – S7*

6.4.2 Interfaces

Having stakeholders who are involved only for part of a system's timespan can be an issue for two reasons. Firstly, a long term stakeholder is more likely to make decisions that positively impact the future resilience of the system. Secondly, if one stakeholder takes over control from another partway through the lifetime of a system, these two stakeholders must define an interface between them, such as a contract. Looking across epochs in the study highlighted interfaces as an important aspect of resilience across many different types of system. These interfaces can take different forms and can be either temporal or structural, as shown in Table 6-5.

Table 6-5: Examples of structural and functional interfaces identified in social and technical systems.

	SOCIAL	TECHNICAL
TEMPORAL	Legal contract between technical specialist and project team	Transition between the planning stage of a building and the implementation
STRUCTURAL	Division between domains in organisational structure of the project team	Physical interface between a lot and the rest of the development

6.4.3 Types of change

The data from the interviews also gave us an insight into how these types of systems can change. The stakeholders gave examples of system change when labelling sub-systems with resilience characteristics. In most cases, it was possible to identify an influence, which initiated the change, and an agent, which enabled the change in response to the influence. Although, the change agents were at times hard to identify. For example, in some cases the influence and change agent appeared to be the same entity, however, on closer inspection there appeared to be a chain of influences and agents. Stakeholder S10 described how they, as architects, accommodated influences – in this case the client changing their mind.

> *'So as we're designing along, believe it or not, the project team changes their mind about things and we have to accommodate it.' – S10*

This description suggests the project team influenced the architect and the architect adapted (with the change agent being internal to the architectural firm). However, the stakeholder then continued explaining this example, saying that the lot they were designing had to accommodate more apartments than initially expected, but the way they designed their lot meant that these extra apartments could be added into the design.

> *'We had to accommodate additional apartments because they couldn't fit them on another lot so our buildings got bigger. But the design proved we could accommodate those changes as we went along.' – S10*

From this description, the situation looks more complicated. It seems that the design requirements for this lot were influenced by other lots. So the project team made a change to the architect's design requirements (i.e. how many apartments they have to fit onto their lot). The project team influenced the architect to accept these design changes but the changes were only possible because the lot design was flexible enough to be changed by the architects.

6.4.4 Resilience characteristics

It should be noted that the choice that stakeholders made about whether a system resists, recovers or changes, was also dependent on their perspective on the system. For example, in the above example, the architect said that the lot design was able to change. Some people could view that change as a recovery – the architect was told the existing design would no longer work, and the architect then had to recover. It is not clear in this study if the stakeholders thought in much depth about the difference between a system recovering and a system changing. There was however some suggestion that when social systems were forced to change – that is they faced a negative external influence – then this was classed as recovery. Whereas, when social systems proactively changed – taking advantage of a new opportunity – then this was classed as changing to accommodate influences.

For all types of system it appeared that when stakeholders were discussing systems that lasted over long periods of time, they were more likely to describe them as 'resisting'. For example, one stakeholder contrasted two types of social systems, saying that resisting influences is an advantage for the long established organisation but that organisations operating at a lower level, on a shorter timescale must change in response to influences.

> *'I actually think that the university is relatively slow to change, but they're very robust in themselves and that's why they have had such longevity. [...] Our [project] team is a bit different. We're not operating at a governance level, we're operating at an executive level. We are charged with delivering something, not over hundreds of years, but over two or ten years so our perspective is different and we need to function quite a bit more flexibly than a lot of the university.' – S7*

In this case, the stakeholder works for the project team running the development project, which they see as separate from the university. However, this project team is in fact employed by and under the direction of the university. Therefore, some stakeholders did not distinguish between the project team and the university and viewed the university as able to change in response to influences.

> *'I think you'd have to say the university resists. Although that said, the university has shown a lot of foresight in doing this development, which is a very evolutionary thing. Yes, I think actually the university can change.' – S11*

These differences in perspective partly depend on how closely involved stakeholders are with a certain system in their daily practice. For example, when stakeholders identified systems in their maps, they grouped together systems that had less impact on their work and broke down systems that were more significant into lower levels of detail. This has implications for assessing resilience, because a system could be incorrectly characterised as unable to change in response to influences by a stakeholder if they are not familiar with that system's function and structure. In fact, all of the stakeholders described themselves or their team as able to change, regardless of how other stakeholders described them, suggesting that there can be small scale changes that only local stakeholders are aware of.

6.4.5 Social and technical systems

Taking a socio-technical approach in this study allowed us to identify and compare the resilience characteristics in social and technical systems. Across the system maps, the distribution of the systems that were labelled as R1 (resist) was equal across social and technical systems. Whereas, for R2 (recover) and R3 (change), 60% of systems allocated with these characteristics were social and 40% were technical. These distributions were reflected in how the stakeholders talked about social systems in contrast to technical systems. Social systems were seen as ‘messy’ and ‘complicated’, but they were also seen as readily able to change.

There was also a difference between social and technical systems in the type of change that was described by stakeholders. In general, social systems were able to change in response to influences without requiring outside intervention; an internal agent facilitates the change. In contrast, when technical systems changed they required an external social system to act as a change agent. This difference in the way that social and technical systems change framed stakeholders’ perspectives on how resilience can be achieved. For example, one stakeholder reasoned that resilience comes from changing stakeholder attitudes, since better decisions will be made about how to design technical systems.

> *‘If you change people's attitudes and the facilities through which those attitudes and decisions and ambitions can be articulated, everything else flows from it. But if you start saying we should have more resilient buildings you’re looking up the wrong end of the pipe.’ – S4*

This view was reflected by 9 of the 11 stakeholders interviewed. They said that social systems, rather than technical systems, contributed most to the resilience of a socio-technical system. The technical systems were perceived as the ‘end product’ created by social systems or the ‘structure’ that supports social systems. Some stakeholders went as far to say that social systems can still be resilient without resilient technical systems.

> *‘If the infrastructure is rubbish you could still get a sense of community, but it might be in adversity.’ – S1*

This is in contrast to technical systems. In the only examples given where a social system proved to not be resilient, the technical systems supporting that social systems were implicated as being negative influences, and the socio-technical system as a whole was deemed to have failed. This suggests that, because stakeholders view the purpose of technical systems to support social systems, these technical systems can only be said to be resilient if the social systems they are designed to support are resilient.

6.5 Findings on using visual methods in interviews

This study is, as far as the author is aware, the first on resilience to use visual methods in interviews with stakeholders. Therefore, it is useful to reflect on the effectiveness of the method used.

There was a marked difference in the conversation content with stakeholders before and after the system mapping exercise was introduced. At the start of the interviews, most stakeholders expressed uncertainty over what resilience, with some stakeholders going as far as to say they were unsure that they would be able to contribute useful data to the study. Once the system map was introduced, these concerns largely disappeared because the stakeholder was given control over the systems they identified in the map and therefore they could talk about parts of the system they knew well. There were a few exceptions to this where stakeholders already had views on resilience and preferred to talk freely rather than use the map.

Although some stakeholders were able to talk about resilience, without the system mapping exercise, the conversations before the mapping was introduced tended to reflect the sentiments found in the project documentation and press releases. One reason for this could be because some stakeholders associated 'resilience' with 'environmental sustainability', which is a politically important subject. This also meant that stakeholders were talking about the development as a place, or product, as it would be when built out and in use. The system mapping exercise moved stakeholders away from giving rehearsed statements, or saying what they thought the researcher wanted to hear, and instead moved the discussion into a breadth of topics spanning a range of timescales across the planning, project, and product stages of the development. Breaking down the system into sub-systems also meant there was comprehensive coverage in the data with concrete examples of resilience across different types of system and levels of abstraction. The three epochs – plan, process and product – emerged from the data so there was less coverage for the 'plan' epoch. For future studies, stakeholders could be sampled to insure more even coverage across all three epochs.

The system mapping exercise was an effective way to relate different perspectives to one another. For example, some stakeholders were focused on parts of the development project, which were not mentioned by other stakeholders. However, using the system maps I found links connecting these stakeholders, with every stakeholder having at least one common sub-system. New connections could also be made at the researcher's discretion by asking stakeholders to integrate specific sub-systems into their system maps. One challenge associated with these connections was that some stakeholders assigned different resilience characteristics to the same sub-system. This could be because of a number of factors including: stakeholders referring to different aspects of the same system, a single system displaying different characteristics at different points in time, or stakeholders disagreeing. However, in this study it was not possible to determine which factor applied in each case. One way this could be achieved in future studies would be to show stakeholders each other's system maps, or to ask stakeholders to co-create maps in workshops.

In the interviews a division between 'people' and 'things' was used to ensure that both social and technical systems were discussed with all of the stakeholders. Whilst this was effective, there is a third type of system, ecological systems, which do not fit easily into the 'people' and 'things' categories. Some stakeholders did mention ecological systems including, 'the environment', 'the climate' and 'animals'. However, there was not enough data in these interviews to evaluate how these ecological systems might be incorporated into the system maps. This was because none of the stakeholders had system purposes that directly related to ecological systems or environmental sustainability. For future studies, this could be addressed by having a third category of sub-system and by sampling to include stakeholders responsible for considering the ecological impact of a socio-technical system.

6.6 Study 3 summary

RQ4: What can we understand about resilience from multiple stakeholder perspectives?

In Study 3, I used the diagrammatic framework developed in Study 2 to compare perspectives on a single socio-technical system to develop our understanding of resilience. This study has shown that resilience is strongly linked to individual stakeholders' perspectives, which can be framed by identifying perceived system boundaries, purposes and timescales. New insights were found about resilience that relate to system interfaces, types of change and interactions between social and technical systems.

Whilst many studies consider the resilience of individual systems from a specific perspective, most large socio-technical systems are really a constellation of systems with many stakeholders each with their own (or many) perspectives. This study has furthered our understanding of stakeholder perspectives on resilience by determining the factors that influence an individual stakeholder's perspective as well as the types of findings that can be gained by using this approach. By comparing and contrasting across stakeholder perspectives on a single socio-technical system, I have shown it is possible to get new insights into what makes a system resilient with respect to system domain, stakeholder purpose, system abstraction, and timescales. I have also explored similarities and differences between technical and social systems.

This study was conducted on a development project, but by categorising the sub-systems broadly into either 'social' or 'technical' and using three overarching resilience characteristics, I expect the findings to be generally applicable across any socio-technical system. The findings of this study are consistent with the findings from Studies 1 and 2, which were conducted across a broader range of system types and domains. This is also confirmed by the consistency of these findings with other domain-specific studies in the literature. For example, the epoch divisions of plan, process and product are common across many designed, or partially designed, systems. The study showed that by taking a systemic approach, we can overcome the problems of communicating with stakeholders across domains, realising new insights into both how to frame stakeholder perspectives on resilience and what these perspectives can reveal about what makes socio-technical systems resilient.

7 Discussion

This thesis was partly developed out of a frustration that resilience was universally acknowledged as an important concept in academia and public discourse and yet there was a lack of practical understanding about how to design for resilience in socio-technical systems. Can we design for resilience by designing products that can adapt? Does resilience require top down social change? In this research I found that before we can answer such questions, we must first develop our understanding of resilience and how it applies to socio-technical systems. I thought that if a conversation was started between academics and system stakeholders then we might gather new insights that bring us closer to the answer of how to design resilient socio-technical systems. Thus, I have addressed the question:

What can we understand about resilience from talking to system stakeholders?

As the research progressed, the main research question was broken down into four sub-questions, each with a corresponding study. Each question emerged based on the findings of the previous study. These questions are shown in Figure 7-1, linked by the findings answering each question.

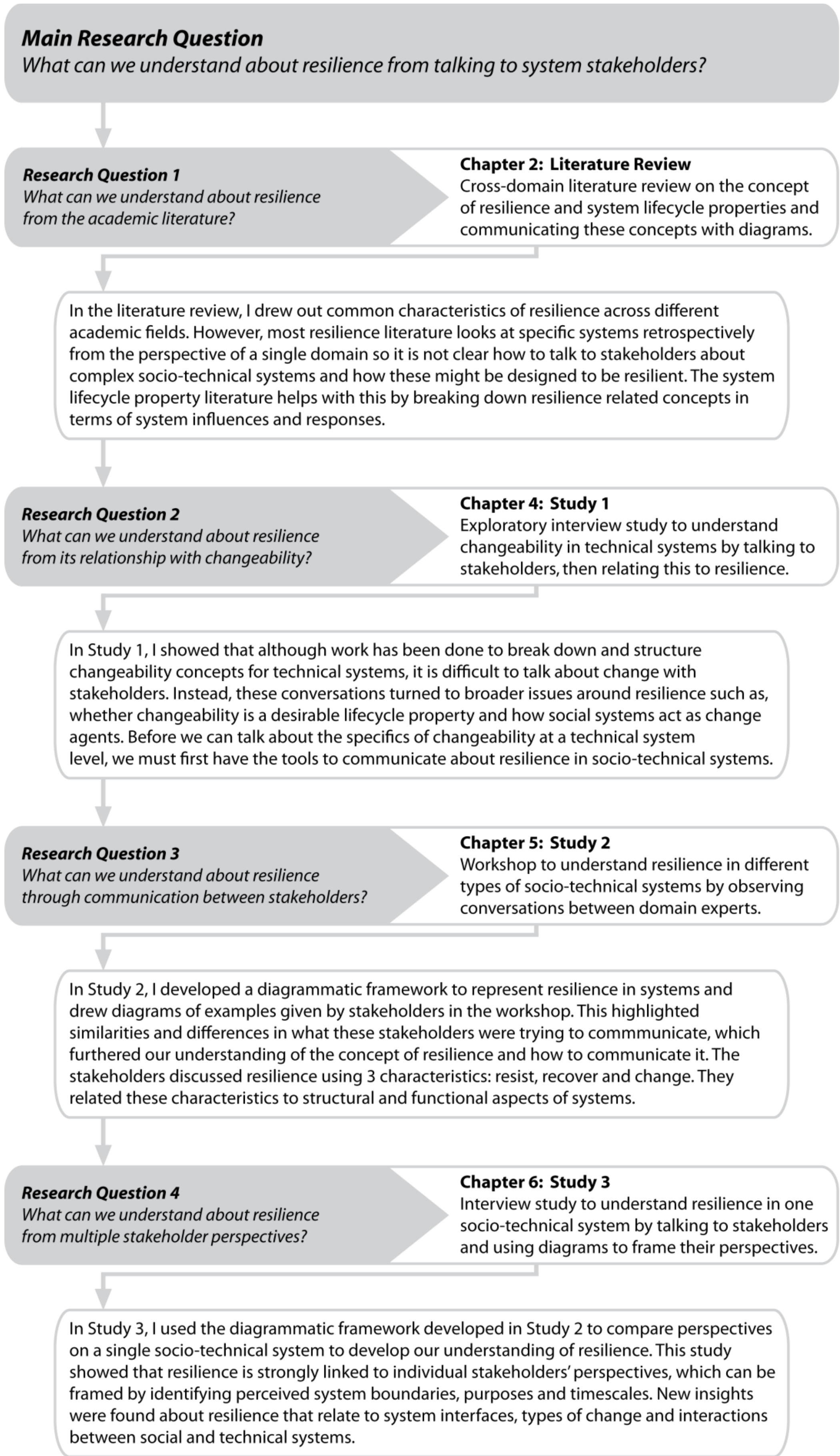


Figure 7-1: Breakdown of research questions and corresponding studies in this thesis with conclusions from each.

I began this research by exploring the concept of changeability, which is central to understanding resilience, by talking to stakeholders of different types of technical systems in Study 1. In design practice, I found that stakeholders are not used to talking about resilience related concepts, particularly changeability, in the context of technical systems. The instances of changeability identified in technical systems tended to be instances of flexibility, that is, if a technical system changed it was because a person in the system had changed it. Not only this, but the confusion over terms, which is discussed at length in the literature, meant that it was difficult to know if I, as the researcher, understood the stakeholders and vice versa. This made it difficult to compare between levels of abstraction and compare diverse stakeholder perspectives. Despite this, many of these stakeholders had similar motivations for wanting – and not wanting – changeability. Also, whereas technical systems were viewed in the traditional design paradigm of engineering robustness, social systems were expected to be changeable, even when this was not seen as a positive system property. From this study it was clear that the resilience of technical systems could not be understood in isolation from social systems, and that to understand the issues around resilience, I should talk to multiple stakeholders across domains and levels of system abstraction.

The second study in this thesis examined resilience from multiple stakeholders' perspectives using a workshop with experts in industry, policy and academia. To overcome some of the barriers of communication experienced in the first study, this study was conducted with stakeholders who were already interested in, and had some knowledge of, resilience. These stakeholders had diverse systems of interest, from terrorist networks to space systems, all of which were socio-technical. By observing the cross-domain discussions taking place between these stakeholders, it was possible to identify three characteristics of resilience that were common across diverse systems: resisting, recovering and changing in response to unexpected influences. For a given system, these resilience characteristics might manifest in different types of sub-system at different levels of abstraction. It is the collective behaviour of sub-systems with different characteristics that leads to overall system resilience. Therefore, in this study I also identified system dimensions that help to structure conversations about complex systems: system boundary, system purpose and system timescale. I then conducted a retrospective analysis on the examples given in the workshop, using these system dimensions to abstract from a specific domain and provide abstract representations of system structures and functions, showing how these examples related to resilience. The conversations taking place in this workshop resulted because these stakeholders were experts in their field in ways that related to resilience. The challenge then was to use this workshop as grounding to generate insights with stakeholders who had no prior knowledge of resilience.

Using the findings from Study 2, I developed a system mapping exercise that could be used to communicate with diverse, cross-domain stakeholders. I then used this method, in Study 3, to interview a group of stakeholders involved with a socio-technical system, in this case a city development. This study showed that stakeholders of a single system can have very different perspectives and that comparing these perspectives can lead to new insights about resilience. These insights can increase our understanding of the structure and function of a socio-technical system and mechanisms of change within that system. A socio-technical approach is needed when looking at resilience because technical systems are designed for a purpose that is defined by social systems.

In the rest of this chapter, the findings from the empirical studies will be discussed against the academic literature to determine the core contributions that have been made. From the literature it was clear that the issue underlying research on resilience, and related system lifecycle properties, is a semantic one. Definitions of resilience are unclear and inconsistent, which is a problem for someone who wants to talk to cross-domain stakeholders. Therefore the first issue that must be discussed here, is what this thesis adds to existing work on resilience as a concept (7.1). The second section in this discussion (7.2) looks at a theme that is central to this research but is not well addressed in the literature, which is stakeholder perspectives. Here I reflect on why considering multiple stakeholders is important in resilience research, and what has been learnt from taking this cross-domain approach. This research has used visual methods as both an ideation and a communication tool. Therefore, the third section in this chapter (7.3) discusses how diagrams in the literature were built upon and used for presenting and generating research data. The fourth section (7.4) evaluates this research against measures of validity. Finally, the limitations of this work are discussed and suggestions made for future work (7.5).

7.1 Understanding what resilience means

At the start of this research I looked at resilience as just one of a group of system lifecycle properties. As I began to deconstruct what these lifecycle properties meant and how they compared to one another, resilience became a problematic concept because it did not fit into classifications as simply as the other lifecycle properties. Resilience cannot be distinguished from other system lifecycle properties based on a specific system structure or behaviour, rather it is an overarching, multi-dimensional concept. I realised that a resilient system is one that survives because of an amalgamation of sub-systems with different structures, types and behaviours, and that changeability is just one part of what makes up a resilient system. Here I will first discuss the characteristics of resilience and then relate resilience to important dimensions of socio-technical systems.

Whilst resilience characteristics and definitions of resilience are well discussed in the literature, I am not aware of any literature that has comprehensively discussed resilience (or other system lifecycle properties) in terms of the dimensions of socio-technical systems, such as purpose, timescale and level of abstraction. In Study 1, the interviews were ostensibly about changeability in technical systems however the stakeholders had not heard of terminology like changeability and it was difficult to know if we understood each other when using these terms. Despite this, it was clear across all of the studies that the people I spoke to had a unique perspective on the systems that they were stakeholder of. These perspectives were driven by a complicated set of factors relating to what they thought the purpose of the system was, how long they would be a stakeholder of that system, and their boundary of control, influence or understanding. In this research, I found that thinking about resilience beyond a definition or set of characteristics helped to overcome semantic barriers by facilitating structured dialogue. Although mentions of various system dimensions can be found in the resilience literature, I am not aware of any research where they are presented clearly or used to compare different types of systems or instances of resilience. Here I will discuss both the characteristics of resilience and relate these to system dimensions.

In this research the term resilience is defined as an overarching concept, including other system lifecycle properties such as robustness, flexibility and adaptability. However, it is worth noting that some authors define resilience more narrowly. Other stances include seeing ecological resilience as distinct from engineering resilience (Holling, 1996), or preferring to use terms such as agility (Haberfellner & de Weck, 2005) or antifragility (Taleb, 2012). My decision to use resilience in preference to these other terms, is because resilience is the only term that is used widely across domains including disaster risk management (MacAskill & Guthrie, 2014), community studies

(Baek, Meroni, & Manzini, 2015), economics (Simmie & Martin, 2010), and psychology (Johnson et al., 2016). My work is also outward looking. In Study 1 I found that stakeholders were reluctant to engage with some words, such as 'changeability', because they did not feel they understood it. By contrast resilience is a word that is used in common parlance and that most people are familiar with so, even if stakeholders have different interpretations of its exact meaning, it starts conversations.

7.1.1 Resilience characteristics

In the literature review (Chapter 2), the meaning of the term resilience was discussed starting with its origins in the field of socio-ecological systems, moving across domains including organisational science, disaster management and engineering. There is confusion in the literature over what resilience means because it is in fact a term that encompasses a set of ideas, or characteristics. In the literature review I looked at characteristics of resilience that authors identified for societal resilience (Dovers & Handmer, 1992), seismic resilience (Bruneau et al., 2003), supply chain resilience (Ponomarov & Holcomb, 2009), and engineering resilience (Westrum, 2006). Across these authors there were five characteristics of resilience: prevention, impact minimisation, recovery, incremental change, and adaptability. Comparing which of these characteristics were used by authors when describing resilience showed that these domains each used the term with a different emphasis. In the literature review I suggested that this could be attributed to the aims of each field and the purpose of the systems they are studying.

In all of the empirical studies, stakeholders discussed issues relating to the five resilience characteristics that were identified in the literature. In Study 2 (Chapter 5), these five characteristics were refined to three core characteristics: resilience as *resisting* influences, resilience as *recovering* from influences and resilience as *changing* to accommodate influences. These three characteristics are consistent with some authors' characterisations, for example in (Bhamra et al., 2011). In Table 7-1, these characteristics have been matched to the five categories identified across domains in the literature review, with 'resisting' including prevention and impact minimisation, and 'changing' including incremental change and adaptability.

Table 7-1: Table showing characteristics of resilience across domains, relating characteristics from the literature to the three characteristics defined in this thesis.

	R1		R2	R3	
	PREVENTION	IMPACT MINIMISATION	RECOVERY	INCREMENTAL CHANGE	ADAPTABILITY
SOCIETAL RESILIENCE (Dovers & Handmer, 1992)	'Resistance and maintenance'			'Change at the margins'	'Openness and adaptability'
SEISMIC RESILIENCE (Bruneau et al., 2003)	'Reduced failure probabilities'	'Reduced consequences from failures'	'Reduced time to recovery'		
SUPPLY CHAIN RESILIENCE (Ponomarov & Holcomb, 2009)	'Readiness and preparedness'		'Recovery or adjustment'		'Response and adaption'
ENGINEERING RESILIENCE (Westrum, 2006)	'The ability to prevent something bad from happening'	'The ability to prevent something bad from becoming worse'	'The ability to recover from something bad once it has happened'		

Study 2 showed that using broad characterisations is useful when talking to stakeholders. For example, the stakeholders in the workshop tended to describe aspects of resilience at this high level and then used examples to illustrate more specific behaviour. For example, saying that a system changed, then outlining what in the system changed and how.

7.1.2 Relating resilience to system dimensions

In the literature it was clear that system attributes are important in understanding and defining system lifecycle properties, mainly because certain architectural attributes lead to resilience (as summarised in Table 2-3). In Study 1, I built on this work by finding examples of product structures that enable changeability, an important part of resilience. This work has the potential to lead to strategies for designing resilience into systems. However, it is apparent that there is a link missing; it does not make sense to talk about architectural attributes before addressing more fundamental dimensions of systems. These dimensions include: system type, system purpose, level of abstraction, and time.

By sampling across these dimensions in Studies 2 and 3, I have been able to study resilience concepts in a variety of real world applications and contexts. This can be seen by comparing this research to the conceptual framework developed by MacAskill and Guthrie (2014), shown in Figure 7-2. I have covered all of the categories in this framework. As the authors of this framework point out, few resilience studies cover all of the application categories, which is necessary for a holistic study. Although, in the case of 'chronological', since this research is not limited to the field of disaster management, I have dealt with a broader range of influences. For this framework to be generalised to socio-technical systems, the 'societal' category could be expanded to include organisational contexts with different levels of technology sophistication. Also, my research has shown that it is important to look at socio-technical systems at smaller scales than 'local/community'. For example, resilience is not usually a property that is desirable, or achievable, at a product level but, how product systems, and the social systems interacting with those products, respond to influences affects resilience at higher system levels. This research has demonstrated the importance of such cross-scale interactions in socio-technical systems, building on and extending work in the ecological and social sciences on the concept of panarchy (Allen, Angeler, Garmestani, Gunderson, & Holling, 2014).

Figure 7-2: Conceptual framework of resilience in disaster risk management (MacAskill & Guthrie, 2014).

Understanding these dimensions and relating them to resilience means that fundamental questions about resilient systems can be answered such as: Which system should be resilient? Resilient to what? Resilient over what timescale? Resilient in what way? Once these questions are answered about a socio-technical system, then resilience characteristics can be applied to work out which parts of that system should be changeable and therefore how the system architecture should be designed.

Relating resilience to system type and purpose

Across the empirical studies in this thesis, purpose has 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, the empirical research has shown that some systems are perceived by stakeholders as not having a 'purpose', rather they just exist. For example, as one participant said when describing a city:

> *'I'm not sure that cities have a purpose. I mean, I'm not sure they don't, but I'm certainly not sure they do. I think that cities are rather like human beings, they have intrinsic value and intrinsic worth and they don't have to be justified by what they do or what they aim to do.'*

This raises an important distinction between my work and that in the ecology literature. I 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 I have been studying 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. For example, most organisations are partly designed and partly evolved. 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.

Framing resilience with respect to time

It is necessary to look at resilience in the context of time. In the system lifecycle property literature, this is dealt with by showing systems responding to stimulus over time (Nachtwey, Riedel, & Mueller, 2009). Considering systems over time represents new challenges compared to static analyses used in fields such as robustness engineering (Fitzgerald & Ross, 2012). This added complexity can be managed by dividing up system timelines into segments, or epochs. This approach is being used as the foundation for 'Epoch-Era Analysis', where the 'system era' is the total lifecycle of a system and an 'epoch' is a defined time period where the system has a fixed context and purpose (Fitzgerald & Ross, 2012; McManus et al., 2007; Ross & Rhodes, 2008). I have used a similar approach in Study 3. However, in the literature, epochs are defined for a single system through its operational life, whereas I looked at a nested view of multiple systems and included planning and development stages of systems where applicable. Using epochs overcame the difficulty that some stakeholders had in discussing systems moving continuously through time. Epochs frame the system, so each period can be dealt with separately and the system states can be compared and contrasted between these epochs.

One limitation in using an epoch approach is that complex systems that are constantly changing and considering a system at discrete points in time 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, the definition of an epoch will be perspective dependent. For example, in agile software development, products are built in short sprints with deliverables at the end of each sprint. The product may be in use whilst these sprints take place. One stakeholder could see this as a 'process' epoch whereas another stakeholder could see this as a 'product' epoch (definitions of process and product are used as defined in Chapter 6).

There is not enough attention paid to timescale in the resilience literature. My work has shown that both the actual timescale of a system (e.g. the launch date of a system, or the timing of an influence) and the perceived timescale of a system (e.g. a stakeholder only thinking, or knowing, about a one segment of a system's lifetime), have an impact on how resilience is defined. Neither of these points are well addressed in current literature but my work on defining stakeholder perspectives will help authors to consider system timescales in future studies.

Framing resilience with respect to system abstraction

There are very few discussions of system abstraction in the literature, although one diagram was found showing 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, Eckert, & Clarkson, 2007; Haberfellner & de Weck, 2005; McManus et al., 2007). The empirical work in this thesis confirmed that defining a system boundary is an essential step when understanding and talking about resilience. However, Study 1 (reported in Chapter 4) found that defining, for example, an influence as internal or external was less useful in practice than defining a stakeholder's perspective and level of abstraction within a large complex system. 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 to a stakeholder at managerial level, but it might appear changeable to a technical expert.

7.1.3 Designing for resilience

The aim of this research was not to answer the question of how to design resilient systems. However, this work does provide a conceptual and practical framework to support the process of architecting resilience into complex systems (Maier & Rechtin, 2009). In systems engineering, architecture is used as a way to understand, design and manage complex systems (Crawley et al., 2004). Attempts have been made to link system architectures to system lifecycle properties, for example, by measuring the flexibility of different system architectures (Broniatowski & Moses, 2016) and by linking system lifecycle properties to architectural attributes (Schulz & Fricke, 1999) . In this research, I have also used system attributes to understand resilience concepts. These attributes were first explored in the literature review (Section 2.1.4), with descriptions of six attributes that are related to resilience in the literature: modularity, redundancy, diversity, connectivity, decentralisation, and feedback loops. In Study 1, I discussed attributes found in technical systems, which were predominantly types of modularity, with some mention of redundancy and diversity. Then in Study 3 I identified different types of functional and structural interfaces in socio-technical systems, which cover the four types of system architectures that Levis (1999) identified: functional, physical, technical, and dynamic operational. The system mapping exercise used in Study 3 is not, in its current form, an effective way to identify architectural attributes in socio-technical systems. This is because the types of relationships drawn between sub-systems varied between stakeholders, and there was no strict criteria for whether a relationship between two systems should exist or not. Despite this, perspectives about architectural attributes did emerge from the discussions taking place in interviews. Instead of taking the approach proposed in the systems engineering literature or analysing system architectures with a view to designing systems, I helped stakeholders to map out the structural and functional architectures of their systems, to understand system properties like resilience.

7.2 Taking a multi-stakeholder approach to understanding resilience

This research proposes that to understand and design resilience into real systems, multiple perspectives and multiple types of system across the boundaries of 'social' and 'technical' have to be considered together. The importance of taking a holistic, socio-technical approach has been acknowledged in other fields dealing with complex systems. For example, Complex Product Systems (CoPS) are usually analysed either in terms of product architecture or organisational structure, however, studying both types of system together can reveal design inconsistencies and lead to new insights (Sosa, Eppinger, & Rowles, 2004). In the resilience literature, social and ecological systems are considered together (Adger, 2000; Walker et al., 2002) but technical systems are generally treated separately as part of the system lifecycle property literature. There is however a field dealing with so-called 'socio-technical transitions', which compares new approaches for socio-technical systems to those used in understanding socio-ecological systems (Geels, 2010), and also one example of using a socio-technical systems approach to look at community resilience (Baek et al., 2015). Although this research started from a different point, there are cross overs between my work and that of socio-technical transitions. The approach taken in Study 3, using visual methods with multiple stakeholders of the same system, could be applied in these domains to build upon existing work.

7.2.1 Distinctions and interactions between social and technical systems

In the resilience literature, I looked across domains to understand different perspectives on resilience. I considered how authors in different fields discussed what resilience means, why it is important and how to get it. This approach helped me to develop a better understanding of what resilience means. However, the definitions used within a single paper were mostly from a single domain, framed by an author's background and research aims. These single-domain perspectives are echoed in the way that stakeholders talk about certain types of system. For example, in Study 1 stakeholders talked about technical systems in a way that echoed what is termed *engineering resilience* in the literature. In the literature, this type of resilience is taken to be passive system protection, a system that recovers from or tolerates a perturbation (Chalupnik et al., 2013; Holling, 1996). This is because engineering systems often do not have 'adaptable reserves and flexibility' (Nemeth, 2008), rather they are designed to perform a well-defined function as efficiently and reliably as possible. I have argued that this is one characteristic of resilience, resilience as resisting influences. However, it is not enough for a resilient system to only resist influences, it must also be able to recover and change. In contrast, the stakeholders in Study 1 were happy to talk about social systems in the same terms as what is termed *ecological resilience* in the literature (Holling, 1996). Social systems were seen to exhibit more complex emergent and autonomous behaviours. By taking a socio-technical approach, I have shown that many engineering systems are in fact changeable when considered as part of the social systems they interact with, or rely on. Equally, changes in social systems are reliant on or influenced by technical systems.

The distinction in the literature between social and technical systems largely exists because academics tend to view fields as one or the other. In this research I have blurred the boundary between social resilience and technical resilience, showing that they have similarities and interdependencies. In some cases, even whether a system is predominantly 'social' or 'technical' is a matter of perspective, for example, for an organisational system. One difference between these two categories however, is that social systems can only be decomposed to a level of individual people, and people as individuals are themselves complex systems. This complexity means that it is difficult to assign resilience characteristics to a social system in the same way as for a technical system. For example, international flight networks are socio-technical systems. The technical systems that contribute towards these flight networks can be decomposed into air traffic control systems, airport buildings, aeroplanes and aeroplane engines. An aeroplane engine is a resolvable engineering system and it is designed to be robust. An engine is designed to a specification to cope with all expected flight conditions. If an influence arrives that is outside of that specification the engine will not adapt, it will fail. This is fundamentally different to a person. If an influence arrives that a person is not prepared for, in some cases they will fail (e.g. not complete a task, remove themselves from the situation, or be irrevocably harmed), but in many cases they will adapt or be flexible. People have a capacity to change that standalone technical systems, for the most, part do not have. By extension, this means that one way to get overall system resilience is to increase the resilience of individual people. Whilst social elements increase the difficulty of managing, understanding and implementing socio-technical systems (Norman & Stappers, 2015), they are also central in achieving resilience. My work lays the foundation to identify these opportunities to increase resilience in socio-technical systems, by considering social and technical systems together in the context of stakeholders' design practice.

Taking a socio-technical approach is an effective way to analyse resilience and related concepts, in systems that are more conventionally approached from either a social or technical perspective. For example, in communities (Baek et al., 2015) or infrastructure (Melese et al., 2016). In this study, I have confirmed this finding by demonstrating that a holistic analysis of a socio-technical system reveals new insights into the characteristics of resilience. However, I have built upon the existing literature by identifying a set of parameters that must be considered when taking a systemic design approach to resilience. These include: system domain, stakeholder purpose, system abstraction, and timescales. These factors must be considered from multiple stakeholder viewpoints because how you define a system's resilience is dependent on perspective.

In the resilience literature, the perspectives of individual stakeholders in a socio-technical system are not explored. Despite this, resilience is often defined with respect to a negative outcome or influence, such as 'The ability to prevent something bad from happening' (Westrum, 2006). Whether an outcome or influence is 'bad' is dependent on perspective. Therefore, for a complex socio-technical system with many stakeholders, there will be different perspectives on what resilience means for a specific system. This study also illustrated that each stakeholder can have a localised view of a system. Therefore different stakeholders can view the same system as having different structures, functions and timescales. This means that factors that one stakeholder might identify as increasing resilience, may be viewed by another stakeholder as detrimental to system resilience. This confirms a similar finding that was observed in another study on resilience in communities (Baek et al., 2015).

Although there is some literature that takes a socio-technical approach to researching resilience, these studies tend to be domain-specific. To avoid this, I have identified three characteristics of resilience, which were shown in Chapter 5 to have applicability across domains. These characteristics were then applied to social and technical systems irrespective of domain. In doing this I have demonstrated how social and technical systems display different resilience characteristics and the types of socio-technical interactions that lead to resilience. This has implications for systemic design, offering an approach that can be generalised to understanding resilience in all types of socio-technical systems.

At the beginning of resilience research, a clear distinction was made between ecological resilience and engineering resilience, whereas social resilience was generally seen as equitable to ecological resilience (Adger, 2000; Holling, 1996). Although the boundaries between these definitions have blurred over time, I found evidence that some stakeholders still perceive social and technical systems in a similar way. Social systems were perceived to change readily whereas technical systems were seen as more rigid. It was clear that social systems increase the resilience of socio-technical systems by being adaptable and, at times, technical systems limited the ability of the socio-technical systems to change even when change was desirable. However, stakeholders appeared to be using these properties to structure and control socio-technical system complexity. This was achieved through interfaces. Technical systems acted as interfaces between different social systems, as well as different points in time. These types of trade-offs between resilience characteristics are implied in some resilience studies, but they are not made explicit or related to the system parameters that I have identified here.

7.2.2 Understanding stakeholder perspectives

In the resilience literature, the perspectives of individual stakeholders in a socio-technical system are not explored. Despite this, resilience is often defined with respect to a negative outcome or influence, such as, 'The ability to prevent something bad from happening' (Westrum, 2006). Whether an outcome or influence is 'bad' is dependent on perspective. Therefore, for a complex socio-technical system with many stakeholders, there will be different perspectives on what resilience means for a specific system. Study 3 also illustrated that each stakeholder can have a localised view of a system. Therefore different stakeholders can view the same system as having different structures, functions and timescales. This means that factors that one stakeholder might identify as increasing resilience, may be viewed by another stakeholder as detrimental to system resilience. This confirms a similar finding that was observed in another study on resilience in communities (Baek et al., 2015).

In this thesis, considering multiple perspectives has allowed me to explore resilience across different types of system, and also in the context of real design practice. In the academic literature, perspectives can be clearly defined based on a field of study and system of interest, framed with respect to existing literature. In design practice, defining a stakeholder's perspective is often more difficult. For example, one participant in Study 3 explained that sometimes they thought of their system as a 'project in development' and other times as a 'place in operation'. Therefore, I have studied different aspects and combinations of stakeholder perspectives – from stakeholders of different technical systems, to stakeholders of the same socio-technical system at different levels of abstraction).

Significantly, the meaning of resilience in all dimensions (as listed in Section 7.1.2) is dependent on perspective. This means that we can only discuss resilience in design practice once we define the perspectives of the stakeholders we are talking to. Distinguishing between the subtleties of different perspectives was shown to be difficult in Study 1, and was what drove the move towards using visual methods in subsequent studies. It was found that the key system parameters that need to be defined to understand a stakeholder's perspective and discuss resilience are: boundary, purpose, timeframe and structure. Although these points are touched upon in the literature, I am not aware of anywhere that lists them as prerequisites for communicating with stakeholders about resilience. Nor, are there existing tools in the literature, like my system mapping method, that demonstrate how to frame multiple stakeholder perspectives and have a structured conversation about resilience or even complex systems more generally.

7.3 Resilience diagrams and visual methods

One of the threads running through this research is the use of visual methods to understand resilience and related concepts. Visual methods have been used to achieve more than one aim. To start with, diagrams were a useful part of the literature review. By looking at what academic authors chose to represent about system lifecycle properties and how they achieved this, I could identify the key characteristics of systems that had to be discussed with stakeholders in order to understand change in systems, which is an importance part of resilience. Diagrams also require authors to be clear about issues that do not come across well in textural descriptions, such as how a system boundary is defined. In Study 1 it became apparent that communicating with stakeholders about resilience concepts was difficult. Therefore in Study 2 my use of diagrams progressed, using them as an input into the workshop to help stakeholders communicate, and then to make sense of what stakeholders had said and to relate system examples back to resilience theory. Then, in Study 3, I used diagrams to elicit data from stakeholders, helping them to make sense of resilience and facilitate the discussion without relying on terminology. These approaches contrast to the literature where resilience diagrams are, as far as I am aware, only used to communicate to academic audiences.

One concern when using participatory diagramming is that some participants may find the process of drawing uncomfortable or have poor visual literacy (Crilly et al., 2006; Wheeldon & Faubert, 2009). Reticence was observed in the studies from some participants when the idea of creating a diagram was introduced, although once the process was explained, all stakeholders were able to produce useful outcomes. This was particularly helped by taking the structured approach proposed in Study 3. The visual methods used in this study were similar in style and principle to mapping techniques discussed in the expert knowledge elicitation literature (for a comprehensive review see (Leu & Abbass, 2016)), such as *concept mapping*. However, knowledge elicitation is primarily concerned with mapping conceptual models of processes, situations and human behaviour, whereas this study focused on mapping concrete system elements, without much emphasis on the relationships between elements.

From the literature, I identified three features that characterise system lifecycle property diagrams: system stimulus, system response, and value delivery. Identifying these characteristics was useful in order to distinguish between academic stances and create a framework for defining different types of system lifecycle properties. In the first empirical study, Study 1, visual methods were not used. Based on the literature review findings, I concentrated on discussing changeability using distinctions made by the authors in the literature relating to technical system characteristics. In this study I found that communicating with stakeholders about changeability was difficult and at times confusing. It was particularly difficult to discuss and compare these concepts between different levels of abstraction within systems. For example, even when talking to multiple stakeholders working in the automotive industry, it was unclear how their perspectives related to one another. This problem was compounded in cases where the technical architecture being discussed was complicated and unfamiliar to me, because it was difficult to ask meaningful questions or develop an understanding of the system structure.

In Study 2 I developed a diagrammatic framework for system lifecycle properties, based on the literature and first study findings, which was used and refined with stakeholders through Studies 2 and 3. As the framework evolved, I realised that there is a fundamental difference between discussing system lifecycle properties in academic literature and in design practice. This is because the literature on changeability relies on a clear understanding of how a system is structured and how it behaves. However, for complex systems, no one stakeholder has a view over the whole system and their experience of that system's behaviour and structure is largely based on their individual perspective. For example, based on the literature I defined the difference between flexibility and adaptability to be whether the agent of change is outside or inside the system boundary. However, in practice, this distinction is subjective, based on an individual stakeholder's definition of the system boundary and the location of other systems relative to this boundary. More fundamentally, whether a system was seen to be changeable, and whether changeability was desirable, also depended on stakeholder perspective. Therefore, it became apparent that the primary role that visual methods should play in conversations with stakeholders should be to frame changeability relative to each participant's perspective, using the broader concept of resilience to encompass different aspects of change.

Study 2 involved stakeholders from diverse domains who already had an interest in resilience. These stakeholders had examples of dealing with resilience related concepts in real systems, and they had already come up against the challenges of talking about resilience in interdisciplinary settings. Therefore, seeing how they communicated with each other, and what they identified as important when talking about resilience, allowed me to identify important factors that can be used to structure a conversation about resilience: system boundary, system purpose and stakeholder abstraction. I used the diagrammatic framework to draw examples of resilience described in the literature. The examples could then be abstracted and the common themes drawn out across domains. This approach helped me to overcome the communication issues highlighted in Study 1, however it did not address the problem of connecting two stakeholder perspectives on the same system but at different levels of abstraction.

In some respects, the diagrammatic framework presented in Study 2 is consistent with the academic literature. In the diagrams representing the stakeholders' examples, the system boundary is shown along with an influence either inside or outside of that boundary. In the literature however, there are no diagrams that attempt to simultaneously show system structure and system response over time. I found that including a dimension to show a system's function moving through time was necessary to illustrate how a system responded to the influences described. The other inconsistency is that in the literature, there is an emphasis on change agents, whereas in practice it was difficult to identify where these agents belonged in the workshop examples and so they do not feature on the diagrams. This is because the stakeholders' examples were given at a single, often superficial, level of abstraction without being delved into.

The third empirical study, Study 3, drew together the visual methods developed over the course of this research and used them to address the issue of relating stakeholder perspectives across domains and across levels of abstraction. In these interviews using a system mapping exercise allowed for a more in-depth exploration of system structure and resilience characteristics (Crilly et al., 2006; Kesby, 2000). I also found that using visual methods I could discuss all the issues related to resilience without using specific terminology. This meant that new insights about resilience and changeability could be uncovered without the stakeholders having an awareness of what these concepts are. The stakeholders who were interviewed could talk about the parts of the system they had expert knowledge of, and I as the researcher got a clearer picture of the system structure to probe into. This contrasted to Study 2, where the insights came from conversations between stakeholders who already had knowledge of resilience.

In Study 3, some of the stakeholders I interviewed were used to talking about the system to the public and press, presenting the project in the best light. There was a clear distinction between the freeform conversations that took place at the beginning of the interviews and the conversations that took place using the system mapping exercise. For example, one stakeholder was talking about the sustainability of the development at the start of the interview, but when the system mapping exercise was introduced it became apparent that they were more interested in budgets and delivery timelines. Ultimately, using diagrams helped to reduce stakeholders' reliance on standard answers or practiced narratives (Bagnoli, 2009; Wheeldon & Faubert, 2009). This allowed me to look beyond information presented in design documents and publicly available information, and discover more about individual perspectives on systems.

The visual approach used in this research corresponds with the category of 'diagrams' (Umoquit, Tso, Varga-Atkins, O'Brien, & Wheeldon, 2013). The system maps simplified complex ideas by constraining the number of system elements they could use. To some extent the structure of the maps was pre-determined by using boxes to represent system boundaries and leading the participants through stages using "scaffolding' instructions' (Prosser & Loxley, 2008). However, the participants were given freedom over the written content and spatial arrangement of elements within this structure. Diagrams were particularly helpful in drawing parallels between social and technical systems. In Study 1 there was a marked difference in how stakeholders referred to social and technical systems, with stakeholders talking about social systems with less clarity. Whereas in Study 3 the system mapping exercise required the stakeholders to be explicit about the structure of social systems and interrelationships. The discussions were correspondingly more precise and it appeared to make it as straight forward to talk about the characteristics of social systems as it was for technical systems. Therefore, using visual methods helped to overcome the semantic issues that are referenced throughout the resilience literature.

7.4 Validation

To validate this research, I evaluated it against four measures of 'trustworthiness': credibility, transferability, dependability and confirmability (Lincoln & Guba, 1985). Each of these measures are discussed here in turn.

7.4.1 Credibility

In the data analysis, credibility was achieved by triangulating themes between participants (Denzin, 1989). To ensure this was possible, there were commonalities between participants in each sample. Examples of these commonalities include participants working in the same company, in the same role or on the same system. A case study was chosen for the final interview study focusing on a single project. This meant that the researcher spent enough time immersed in the research setting to build a full understanding of resilient systems in a design context.

This research has been continually subjected to peer debriefing, both within the research group and externally in the academic community. One form of member validation (Bloor & Wood, 2006) used in the final study was adding concepts from one participant's maps to another's and discussing where they fitted in.

7.4.2 Transferability

Attention has been given to explaining the sampling used in each study to allow for other researchers to test and build on this work. Throughout, I have tried to ensure the themes that emerged from the study are not domain-specific, by abstracting them and comparing across domains.

7.4.3 Dependability and confirmability

Care was taken in this research to maintain traceability back to the raw data. In Study 3, double coding was used as a form of 'investigator triangulation' to support the themes drawn from the interviews (Denzin, 1989). This involved the secondary researcher coding half of the interview transcripts. The themes that emerged were compared to the original analysis to ensure its dependability and confirmability, with more details given in Section 6.2.3.

7.5 Limitations and further work

In the interviews conducted in this research, it was assumed that the stakeholders being interviewed would not have thought extensively about resilience (or related concepts) prior to the interview. This meant that it was necessary to make the concepts accessible and for me, as the researcher, to pick up on cues, asking probing questions about systems that I had not necessarily come across before. Whilst this approach appeared to work effectively and sufficient data was collected, it is possible that because the stakeholders did not understand resilience well themselves they may have omitted important information or system examples. By contrast, in the workshop held in Study 2, the stakeholders did already have some understanding of resilience and the quality and frequency of the system examples they offered was high. At first it seemed that this was a product of the workshop setting but the pilot workshop for Study 3 (see Section 6.1) suggested that this method was not as effective with stakeholders who did not have an existing understanding of resilience, with the workshop groups requiring a lot of prompting from the facilitator. Based on this learning, the system mapping exercise in Study 3 could be developed to include a detailed explanation of resilience, and related concepts, for stakeholders being interviewed. This could be delivered at the beginning of the interview or through a briefing document sent to interviewees before the interview takes place. This may also build the stakeholders confidence in answering questions and interacting with the system map. Another way to avoid missing important examples or details would be hold a workshop, with a group of stakeholders of the same system, after one-to-one system mapping interviews. This workshop could be used to compare and contrast system maps and validate the interview findings (Sections 6.3 and 6.4).

In Studies 1 and 2, most of the participants offered accounts of systems and resilience examples that were either in the past or present. In Study 3, because the system of interest was under development, stakeholders gave an increased number of prospective examples of how they expected the system to behave in the future. Retrospective and prospective accounts have trade-offs, and looking across epochs mitigates some of the limitations of participants discussing past, present and future system examples. The epochs that emerged in Study 3 could be used in sampling for future studies, ensuring even coverage of stakeholder interviews over plan, process and product.

My research question was about what we can learn about resilience from talking to system stakeholders. Another approach to answering this question would be to use a longitudinal study of a single system, interviewing stakeholders at multiple points of time, spaced apart and comparing their perspective on resilience over time. This would allow the exploration of stakeholders' perspectives on a system in the past, present and future. This approach would afford the researcher a first-hand account of the system over time, reducing the potential biases that can occur in interviews. The researcher may also be able to monitor system influences and responses to evaluate the system structures and functions that lead to resilience. This would develop on the work done in this research on architectural attributes that lead to resilience characteristics.

Another approach that could be taken would be to facilitate conversations between stakeholders of the same system about resilience. This could be supported with the system mapping framework, asking stakeholders to respond to each other's maps or developing a collaborative map of the system from different perspectives.

For future work, there are also other questions about resilience that could be answered. For example, does artificial intelligence increase or decrease the resilience of socio-technical systems? In this research I have looked across different types of technical system including automotive, software, and infrastructure. For these types of system it appears that although many are flexible, and can change with human intervention, not many are adaptable. There are however emerging areas of technology where technical systems are being designed to adapt and change frequently in use, including artificial intelligence. These new technological innovations would be an interesting area for further studies on resilience, with a focus on passive versus active change. Another area of innovation, which would likely yield new insights into resilience, is the design of technical systems for extreme case environments. For example, whilst it is common in the literature to study communities in developing countries facing environmental and economic uncertainty, there has been little work into the role that technology does, or could, play in increasing resilience of these types of socio-technical systems.

8 Conclusion

When I started this research I wanted to determine how to design resilient socio-technical systems. However, it became clear that this would not be possible because understanding of resilience in socio-technical systems was not developed enough. This was not just a barrier for me as a researcher but also for stakeholders, since to design resilient socio-technical systems, conversations have to take place between practitioners from different domains and perspectives. Therefore, I turned my attention to developing an in-depth understanding of what resilience is and how to talk about it with different types of people.

Taking this approach, I have made the following contributions:

- Identified three characteristics that can be used to talk about the concept of resilience with stakeholders of socio-technical systems: resilience as resisting influences, resilience as recovering from influences and resilience as changing in response to influences.
- Created a framework to understand resilience in the context of the following system dimensions: system type (social/technical), system structure, system function, and level of abstraction.
- Shown how to understand a stakeholder's perspective on resilience based on how they define: system purpose, system boundary, and system timeframe.
- Developed a participatory diagramming method, based on the resilience framework and perspective framing, which can be used to communicate about resilience with diverse stakeholders.

These contributions show that talking to stakeholders has furthered our understanding of resilience and helped to structure a multi-faceted, complicated concept. Whilst talking about resilience was difficult in Study 1, I built on the findings from this Study to work out what the important aspects of resilience are for socio-technical systems and how to talk about them. This meant that in Study 3 it was possible to gain insights into resilience such as, how the structure of a system affects its ability to change. The work done in this research provides the tools and frameworks that stakeholders need to communicate about resilience, which is a prerequisite to designing for resilience. These tools are expected to be generalisable across domains, since they have been drawn from and applied to a wide variety of systems in these studies. These contributions are also useful for researchers in different fields who are interested in the resilience of socio-technical systems. Particularly those who are looking for a structured way to understand and apply resilience characteristics to real life socio-technical systems, working with the stakeholders of those systems.

This research has built on the existing literature about understanding resilience by using cross-domain stakeholder perspectives and visual methods. In the literature I found that resilience is multi-faceted concept that is mainly discussed in the context of social and ecological systems. Elsewhere, related concepts, namely system lifecycle properties, were being discussed in relation to technical systems. By taking a socio-technical approach, I have drawn together different perspectives and developed a systemic approach to understanding resilience that can be applied to further design practice.

There is a reason that in the first study I came up against challenges talking with stakeholders about change in technical systems. Most technical systems are designed to cope with expected influences with defined tolerances, rather than to adapt to unexpected influences without human intervention. Even when adaptation is possible, there will always be types of influences that these technical systems cannot change internally to accommodate. There were many more cases in this research of technical systems that were instead designed to be flexible, with social systems as change agents. Or, social systems adapting to the unexpected and designing new technical systems entirely. Technical systems have a great capacity to add to the robustness and versatility of social systems. However, it seems that the ability of social systems to change is necessary for resilience in technical systems. Therefore, a socio-technical approach to understanding resilience offers the greatest potential for future work on designing socio-technical systems.

In design practice, diagrams are used by stakeholders for many purposes, including generating new ideas, developing concepts, communicating to others, and recording knowledge. The diagrammatic frameworks developed in this research would be a useful tool for stakeholders in all of these pursuits. The process of mapping out system structure from a single perspective, avoids the need for domain-specific terminology and provides a starting point to deal with the complexity of socio-technical systems. In most existing forms of visual representation, social systems are dealt with separately to technical systems. This is also true in conversation. Without the use of visual representations, stakeholders in this research talked about social and technical systems in fundamentally different ways, usually with a preference for discussing one or the other as determined by their domain background. Ensuring that both social and technical systems were included in visual representations of systems brought both types of system into the same discussion. This is useful not just for talking about resilience, but for any conversation between interdisciplinary stakeholders concerning a socio-technical system.

There is a saying that the best way to make sure you understand something is to explain it to others. Every conversation I have had with stakeholders has made me think deeper about what resilience means. Throughout this research, I have structured and restructured mental – and diagrammatic – frameworks. This process has allowed me to make practical contributions towards understanding resilience as a set of concepts that can be discussed in a structured way. One of the central themes in this work is that resilience in socio-technical systems is perspective dependent. There is no right or wrong way to achieve resilience. The strength of different approaches depends on what the stakeholders of that system want, and what they are prepared to give. Therefore, I see resilience as a mind-set. If all of the stakeholders in a socio-technical system can talk about resilience in the context of a defined perspective, I believe that the system overall will benefit. The people in that system will become inherently more resilient, and by extension, over time, the technical systems will be designed and redesigned to better accommodate change and uncertainty.

Resilience is a property of systems that allows them to thrive in the long term. Describing this property as the ability to resist change or the ability to 'bounce back' from adversity is to underplay how important change is in socio-technical systems. Not just reactive change, but proactive change. This is the difference alluded to in the title of this thesis – change or be changed. Understanding this difference is not straightforward. This is partly because of the complexity of socio-technical systems, but also the fact that any one stakeholder has an incomplete view of that system. Understanding change requires looking at a system's function and structure across both social and technical components. It also requires being able to communicate with multiple stakeholders in order to understand different perspectives on that system. Whereas resilience is usually thought of in terms of reactive change, I hope that my research provides a new understanding of resilience as the ability of a system to proactively change, and therefore how we might design for resilience.

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