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Are wildcard events on infrastructure systems opportunities for transformational change?

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ABSTRACT

Infrastructure systems face a number of pressing challenges relating to demographics, environment, finance and governance pressures. Furthermore, infrastructure mediates the way in which everyday lives are conducted; their form and function creating a persistence of unsustainable practice and behaviour that cannot be changed even if change is desired. There is a need to find means by which this obduracy can be broken so that new, more sustainable futures can be planned. This paper develops a methodology, taking concepts from both engineering and social science. Wild cards, or physical disruptions, are used to 'destructively test' complex infrastructure systems and the multi-level perspective is used as a framework for analysing the resulting data. This methodology was used to examine a number of case studies, and with focus groups consisting of a range of different infrastructure providers and managers, to gain a better understanding of systems' socio-technical characteristics and behaviours. A number of impactful 'intervention points' emerged that offered the opportunity to promote radical changes towards configurations of infrastructure systems that provide for 'less' physical infrastructure. This paper also examines the utility of wild cards as enablers of transition to these 'less' configurations and demonstrates how a 'wild card scenario' can be used to co-design infrastructure adaptation from with both infrastructure providers and users.

1. Introduction and challenges for infrastructure

In many developed countries national infrastructure is reaching a critical condition from physical decay, increasing interdependence, and changing demand and operation. Conversely, in rapidly growing economies, investment in new infrastructure is increasing. However, both developed and developing countries face similar challenges and pressures from population growth, changing demands, financial constraints, technological developments and climate change adaptation and mitigation targets. In the UK, the picture in the developed world has been captured by the Council for Science and Technology (2009, p. 4), who have stated that national infrastructure could not continue on its current trajectory because: '*it is less resilient to systemic failure due to ageing components, greater complexity and interconnectivity between different sectors and due to it approaching maximum capacity as a result of increased social and economic pressures; significant challenges of*

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climate change and socio-demographic change mean there is an urgent need to devise low carbon solutions to meet national reduction targets, infrastructure needs to be future-proofed against extreme natural events and future demographic, social and life style changes; its delivery and governance is highly fragmented i.e. *different sectors are managed in silos, investment is ad hoc, typically at times of crisis, there is no overall vision*'.

Furthermore, to function effectively, society relies on infrastructure networks to provide public services, enhancing quality of life, generating private profits and aiding economic growth (Boin & McConnell, 2007). At the national level, telecommunications, emergency services, energy, finance, food, government, health, transport and water sectors provide these essential services. In each of these sectors, components are described as being 'critical' in that if they were compromised or lost there would be a detrimental effect on the service they provide, which could potentially lead to loss of life, severe economic or social consequences. Often referred to as lifeline services, critical infrastructure typically refers to energy, water, transportation, waste disposal and telecommunication systems (O'Rourke, 2007). Critical infrastructure involves large scale, spatially distributed, complex and multi-dimensional technologies, information, processes and actors, creating a system of systems with both engineering (physical components and technologies) and behavioural properties (behaviour of an infrastructure and properties that emerge from factors such as business processes, decision points, human intervention and information generation, availability and flow (Johansson & Hassel, 2010; Tolone, 2009). Critical infrastructure systems appear to be expanding following technological advances and increasing demand, adding new critical elements, and connectivity of infrastructure components (Egan, 2007).

The challenges facing infrastructure sectors in the coming decades and its current vulnerabilities may also be regarded as intrinsically socio-technical. Over time infrastructure systems have become increasingly interconnected, exhibiting functional, physical, budgetary, market and economic interdependencies (Zhang & Peeta, 2011). To these interdependencies we can add those emerging from the social embeddedness of infrastructure, and their dependency from social perception and cultural practices (Granovetter, 1985). Ageing infrastructure is a common problem which causes both technical issues (e.g. reduced performance of construction materials) and social problems (e.g. demand exceeding capacity) that are likely to become more apparent in the near future. For example, London's sewage and water supply system was designed on the basis of a population several times the London population at the time (CST, 2009). Today 40% of London's water mains are over 100 years old, and 12% are more than 150 years old (Thames Water, 2013) leading to problems of leakage due to the degradation of the lining systems of supply pipes and capacity issues of storm water and waste pipes. Furthermore, the problem of ageing infrastructure is compounded by an inadequate infrastructure supply and unequal access to urban services, particularly in the least developed countries where there are large shortages of infrastructure. Given the long lead time to plan, design and construct new components of infrastructure systems, it is important to ensure that they are adequate for, and resilient to, future societal demands. In addition, given the longevity of physical assets a strategic approach to planning and design is necessary. Lifespans of various infrastructure components vary between 15 and 60 years which indicate the timeframes that should be considered in infrastructure planning. Infrastructure design should be orientated towards meeting future population growth, address the needs of migrant and ageing populations and provide greater choice for people in terms of where they live and work (CST, 2009). Urbanisation may demand new infrastructure which is constrained by and has to function alongside existing infrastructure, providing opportunities to address issues of resilience and redundancy arising from interdependencies (Zhang & Peeta, 2011). Infrastructure will require system-based adaptation that considers interdependencies to maximise capacity and enhance longevity.

The need to adapt is further highlighted by natural disasters and extreme weather events which have severely impacted infrastructure systems. For example, in 2010 the Eyjafjallajökull volcano in Iceland caused significant impact on aviation, with more than 100,000 flights being cancelled, more than \$1.7 billion in lost revenues for airlines and more than 10 million stranded passengers (Bolic & Sivcev, 2011); in 2005 Hurricane Katrina destroyed more than 65,300 homes, affected over 200 public water treatment systems in Mississippi, and also affected electricity supply and telecommunications (Levy et al., 2010). Projections of climate change may increase the risks to infrastructure systems (RAEng, 2011; Infrastructure UK, 2011). Systems must be adaptable to long term effects such as sea level rise, and at the same time to extreme weather events such as flooding and heatwaves. Infrastructure also has a major role on greenhouse gas mitigation targets. The energy and transportation sectors are heavily carbon intensive; new technologies and configurations could drastically contribute to mitigation efforts. The provision of infrastructure can also induce changes in demographics and behaviour which may also aid emission reduction targets.

Hence the need to adapt is urgent for many reasons, in addition, in developed nations it is clear that we cannot go on growing our traditional infrastructures as a means of stimulating and supporting economic growth forever due to the constraints of, for example, space, availability of resources such as materials and fuel, environmental degradation and greenhouse gas emissions (e.g. Dawson, 2007). Therefore, there is a need to start thinking differently and at some point we will need to consider less. However, 'less' in this context is both difficult to consider and difficult to achieve due to the inherent obduracy of infrastructure and the built environment in general. We only have to consider the lasting legacy of Roman infrastructure and the way it has shaped our towns and cities to understand how difficult it is to start again, rather than keep adding to what is already present.

These challenges described above highlight several things. Firstly, that infrastructure is inherently a socio-technical system (or system of systems) and as such should be studied from this perspective. Methodologies developed by integrating social science and engineering are required to reconsider the provision and service that infrastructure provides. Furthermore, it is evident that infrastructure systems are not simply components of physical assets, but complex increasingly interdependent, sometimes fragile, but overwhelmingly obdurate, socio-technical systems in which unpredictable failure can cause far-reaching engineering, ecological, economic, social and governance consequences. These system of systems require adaptation to a number of (conflicting) current and future demands and constraints; re-configuration to achieve a sustainable infrastructure transition. Traditional thinking, which equates economic growth with infrastructure build cannot hold true indefinitely and rethinking is required. In order to achieve this, new methodologies are required which integrate engineering and social science thinking and approaches to envisage powerful means of reduction required to create transition to less.

This paper proposes that wildcard events can be used to: better understand infrastructure as a socio-technical system; envision future, more sustainable infrastructure provision; and help co-design adaptation measures with multiple stakeholders. The first section of the work presented in this paper develops an integrated methodology for the analysis of infrastructure systems, using a combination of 'multi-level perspective' (MLP) (e.g.; Geels & Schot, 2007) and the engineering approach of gaining understanding by 'breaking'. Wildcard events were used as a ready means of 'breaking' the infrastructure system to gain further understanding of system behaviour; MLP was used to analyse a number of different historical wildcard events. The second section of the paper examines the extent to which such events could be used as a mechanism for creating transition in infrastructure systems and help envision what less might look like. The last section of the paper will show how the results from the first two stages was used to develop a synthetic wild-card scenario which was used to help sets of stakeholders co-design adaption of infrastructure to climate change.

2. Development of a socio-technical methodology

2.1. A framework to analyse wildcard events

Co-evolution of socio-technical systems examined through historical studies (Geels & Schot, 2007) highlight the processes which cause stability and change in systems, using the multi-level perspective (MLP). The MLP comprises of three levels, with increasing degrees of stability (see Fig. 1). The regime is the dominant system, containing elements that stabilise and structures that determine the fulfilment of specific functions. Components of the existing system may include material components, current technologies, policies and cultures. The regime is embedded within the external landscape where elements can influence the system. At the niche level, actors develop a range of technological, policy and social innovations. Interactions between the landscape, regime and niches determine regime trajectories. Transition pathways are mechanisms that force a shift away from the current trajectory. Geels and Schot (2010) identified these as: breakthroughs and adjustments in the current regime (moderate landscape pressure, but niche-innovations not fully developed will lead to regime actors modifying the current regime); emergence of multiple niche innovations into the regime (sudden landscape change causing regime issues, yet no clear niche innovation to dominate at that time); niche innovation become mainstream (landscape pressure coinciding with sufficiently developed niche innovation); selective adoption of innovations which results in regime changes (niches initially adopted into the regime to solve local problems). The MLP advocates that niche innovation is central to altering the regime of socio-technical systems. However, this depends on pressures from or shocks at

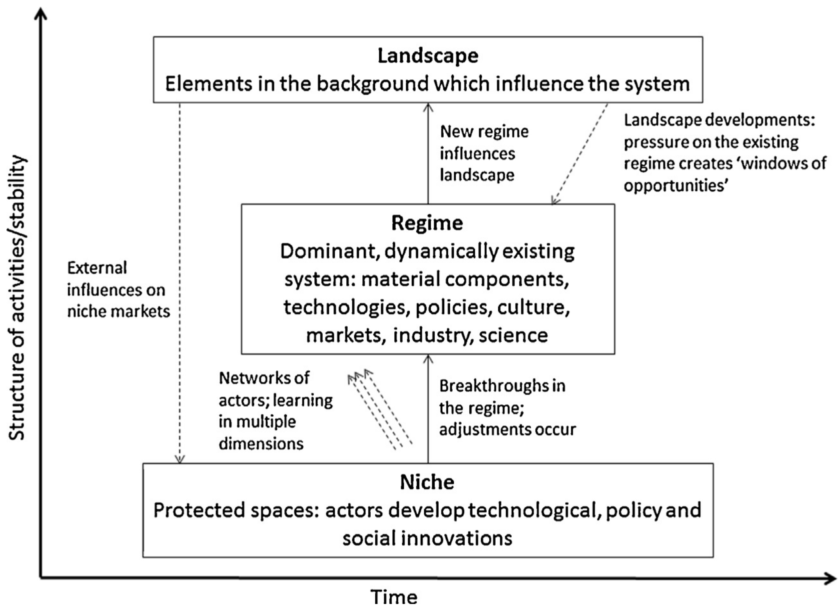

Fig. 1. Multi level perspective.
Adapted from Geels (2002, 2005).

the landscape level for an opportunity to breakthrough into the regime. For example, in the UK, the niche innovation of the electric car's gradual breakthrough into road transport regime has arguably been facilitated by Act of Parliament on Clean Air (Great Britain, 1993, chap. 11), climate change mitigation targets (Climate Change Act, Great Britain, 2008), cost of fuel and promotion of smart technologies (e.g. Dikj, Orsat, & Kemp, 2013).

2.2. Emergence of intervention points

Two focus groups took place with a range of different infrastructure providers and managers to ascertain how shocks to infrastructure systems may aid the re-evaluation and re-thinking of infrastructure provision. During the focus groups, participants were introduced to the Multi Level Perspective described above and a narrative of the major flood events that occurred in the UK during the summer of 2007 was presented. Subsequent discussion led to the mapping of infrastructure systems using the MLP framework and categories that included: physical structures, institutional and organisational factors, social and cultural practices, procedures and tasks, ecological flows and environment, and materials and technologies. Furthermore, identification of various impactful intervention points which arise as a result of wildcard events which could lead to transition within the discussed infrastructure systems, arose. These were then tested against a range of case studies of past events and the extent to which they transformed or altered the system or systems they affected have been evaluated. This approach has similarities with Causal Layered Analysis which itself provides a vertical consideration of futures by considering the past and current; for example, Inayatullah (2004) illustrated using case studies Causal Layered Analysis can be used in developing more effective, inclusive, longer-term policies.

3. Results and discussion – evaluation of intervention points

In the following section, each intervention point is described, and illustrated using past wildcard events, which also demonstrate the challenges to infrastructure systems described earlier. These events are summarised in Table 1. Wildcard

Table 1
Summary of wildcard events analysed.

Event	Cause of event	Infrastructure directly impacted	Knock-on infrastructure impacts	Intervention point
World Trade Centre, New York, USA, 9 September 2001	Terrorist attack	Local emergency services, public transportation, water supply, telecommunications, electric power, finance sector	Subway transportation halted Air transport grounded	Disruption of the current regime prompted change at the landscape level and innovation at the niche level. Learning at the international scale
Hatfield rail crash, UK, 17 October 2000	Train derailment	Closure of railway lines. Speed restrictions on the entire rail network.	Congestion on highways. Significant disruption on a majority of the national network for more than a year.	Disruption of the current regime prompted change at the landscape level.
King's Cross Railway Station Fire, UK, 18 November 1987	Fire	Physical damage to the platform, 3escalators needed replacing.	Northern line service to King's Cross station suspended for 14 months.	Learning across the system.
Japan earthquake, 11 March 2011	Earthquake causing tsunami wave,	Building and infrastructure damage, nuclear incidents including radiation releases.	Germany–nuclear programme	Disruption of the current regime required immediate behaviour change and prompted change at the landscape level. Learning at the international scale–re-evaluation of the provision of infrastructure.
UK Summer 2007 floods, June and July 2007	Series of pluvial and fluvial flooding.	Road and rail systems. Water Treatment Works. Electricity substations.	350,000 people without water supply for two weeks. Water disrupted.	Disruption of the current regime prompted change at the landscape level and innovation at the niche level. Cross-infrastructure learning and improved co-operation.
Northeast US power outage, 14 August 2003	Power surge triggered by extreme heat	50 million people without power	Power generation, water supply, rail transportation, international air transport, financial markets, communication, industry	Disruption of the current regime prompted change at the landscape level.
Workington floods, November 2009	Fluvial flooding	Main road bridge destroyed.	Businesses	Disruption of the current regime led to re-evaluation of the provision of infrastructure and induced behavioural change.

events were chosen to demonstrate each intervention point; it should be recognised that not all events will lead to change or learning within infrastructure systems (Castán Broto, Glendinning, Dewberry, Walsh, & Powell, 2014).

3.1. Wildcard events disrupt the current regime

As described above the regime i.e. components of current infrastructure systems, can be disrupted by innovations at the niche level breaking through into the regime or more commonly, by influences occurring at the landscape level to which the regime has to adjust. Typically the regime is seen as being rigid, however, shocks can disrupt the current norm leading to an improved configuration of the system.

The Hatfield rail crash, which occurred in the UK in 2000 caused the death of four people, seriously injured four people and injured seventy people (Beale, 2002). The immediately enforced speed restrictions and track replacement works caused significant disruption on a majority of the national network for more than a year and many passengers avoided trains and relied on personal cars, causing congestion on the highways. The actual physical cause of the derailment was a broken rail, although subsequent investigations revealed that both poor maintenance and management of the railways in the UK also contributed. Great Britain's railways were privatised (previously British Rail) in the mid-1990s by franchising passenger services, transferring passenger rolling stock to three leasing companies, selling seven, mostly profitable, rail freight businesses, and creating a separate infrastructure company, Railtrack, later replaced by Network Rail which levies access charges on trains (Gibb, 1996). This privatisation, at the landscape level, led to a major disruption in the regime of the railway sector, making it unstable. Wolmar (2005) argues that the derailment exposed the short comings of privatised national rail infrastructure and highlights that staff were not trained adequately to detect defections on the rails, there was no asset register available to the infrastructure company, both in-house knowledge and experience were lost when British Rail was privatised, safety equipment was not fit for purpose, profit margins were affecting observation and maintenance regimes and human error also contributed. The UK Government forced the company into administration and in 2002 replaced it with the not-for-dividend company Network Rail, thereby reversing the change at the landscape level to stabilise the regime once again.

Another example of a wildcard inducing change at the landscape level is the Northeast United States' largest power blackout in North American history which occurred on 14 August 2003, which affected an estimated 50 million people and 61,800 megawatts of electric load in the states of Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut and New Jersey, and the Canadian province of Ontario (U.S.-Canada Power System Outage Task Force 2006). As described by the U.S.-Canada Power System Outage Task Force (2006) the blackout was initiated by overgrown trees brushing against a high-voltage power line in northern Ohio. The softening of line should have tripped an alarm, but the alarm system failed. Three additional lines sagged into trees, switched off and forced other power lines to carry the power, which ultimately also cut out tripping a cascade of failures. The cause of this shock was human error and equipment failure. The estimated cost of the blackout was between $4 billion and $10 billion, in the United States; in Canada, gross domestic product was down 0.7% in August, there was a net loss of 18.9 million work hours, and manufacturing shipments in Ontario were down $2.3 billion. Following an investigation, Congress passed the Energy Policy Act of 2005, which expanded the role of the Federal Energy Regulatory Commission (FERC) by requiring it to solicit, approve and enforce new reliability standards from the North American Electricity Reliability Corporation, previously these were voluntary.

The attacks on the World Trade Centre, New York not only provide an example of how wildcards can enable niche innovations but also highlight how these events can affected multiple infrastructure systems and their affects can spread geographically. The events of 11 September 2001 affected a range of infrastructures in the surrounding vicinity to varying degrees following the initial impact, as well as national and international transportation – suspension of subway transportation and air travel. Mendonça and Wallace (2006) explored data on disruptions to services provided by critical infrastructure following the World Trade Centre attack. Following the initial impact which affected emergency services, ground and air transportation, power supplies, telecommunications, water supply, government services and the financial sector, in the following weeks the attack had differential impacts across infrastructures over time. In week 1, most disruptions affected transportation, government services and banking, while in weeks 2–13 after the event, disruptions to banking were greater. This event highlights the physical interdependency of infrastructure around the area of the main impact. At the national level, the President created the Office of Homeland Security, the Homeland Security Council and Department of Homeland Security for overall coordination of critical infrastructure protection activities. In addition, there was an impact at the international level with fear a similar attack would occur elsewhere. This led to learning that took place at the international level, and the landscape level for the air transportation sector with heightened security regulations which changed the regime e.g. cockpit doors of aircraft are strengthened and bulletproof, improved security screening. Further restrictions were introduced in August 2006 following a threat from liquid explosives. The requirement for improved security checks opened a pathway for technological innovation at the niche level to aid the new security requirements. However, the innovation was not available at the time of the landscape change, yet albeit nearly 10 years later, advanced imaging technology is now part of the regime of airport security in many international airports.

3.2. Wildcards provide opportunities for learning

Past events reveal examples of learning, not just for the particular infrastructure system affected but also across different geographical regions and different infrastructures.

The King's Cross Railway Station Fire, UK, 18 November 1987, was a relatively geographically isolated event. The fire was started by a discarded match on a wooden escalator, which set light to accumulated rubbish, debris and grease (Wharton, 1992). The fire was exacerbated by a solvent-based paint used on the ceiling above the escalator. The fire caused physical damage to the Northern line platform at the station and three escalators needed replacing. The Northern line service to King's Cross station was suspended for 14 months. Following this shock, lessons learnt and changes made were: replacement of all wooden escalators in sub-surface Underground stations were replaced with metal ones, mandatory installation of automatic fire sprinklers and heat detectors in escalators, mandatory annual fire safety training for all station staff, improvements in co-ordination with emergency services and stringent restrictions on the types of paint permitted for use on the Underground (Crossland, 1992). Despite being isolated geographically the lessons learned from this event have been implemented in the wider underground transportation systems' regime.

The summer 2007 floods in the UK affected large parts of the country, but most significantly in the Gloucestershire area. Flooding initially arose from intense rainfall that affected homes, businesses, major roads, railways and the emergency services. Subsequent fluvial flooding overwhelmed a water treatment works which ultimately was closed down, resulting in the loss of direct water supply to 350,000 people for two weeks. At the same time two electricity substations were under threat, one of which serves 600,000 people. Military assistance was required to build a temporary flood defence to prevent the loss of the functioning of this station. For both instances of flooding, the rescue stage, clean-up stage and aftermath in terms of water needing to be distributed via bowsers and bottles required resources from outside of the immediate area (Environment Agency, 2007). The Government responded to the events by increasing funding for flood defences, commissioning a review to the response to the flooding, recommendations from which were implemented by a new Flood and Water Management Act 2010 (Great Britain, 2010). The recommendations from the independent review conducted by Pitt following the 2007 floods, provided learning on a number of levels enabling both niche innovations and landscape change. For example, the phasing out of sandbags, as they were found to be of limited use in protecting homes, enabled other niche level innovation such as flood boards to penetrate the regime; at the regime level, the automatic right to connect surface water drainage of new developments to the sewerage system was removed; at the landscape level, it was suggested that the Government should develop a scheme which allows and encourages local communities to invest in flood risk management measures (Cabinet Office, 2008). The Pitt Review also recommended a flooding exercise to test the effectiveness of new arrangements to deal with flooding and other infrastructure emergencies, and event which facilitated further learning.

3.3. Wildcard events facilitate co-operation and collaboration of multiple infrastructure providers

Major wildcard events can impact multiple infrastructure systems. The immediate response brings together managers of these different infrastructure providers thereby providing an opportunity for collective learning and knowledge exchange. In the UK during major incidents, the hierarchical gold–silver–bronze command structure is implemented by the emergency services, which corresponds to the strategic, tactical and operational activities (National Policy Improvement Agency, 2009). The membership of these groups depends on the nature of the shock. The immediate impact of the UK summer 2007 floods required not only the emergency services to co-operate and co-ordinate under the command structure but also major infrastructure providers (e.g. Severn Trent Water, National Grid), local councils and government organisations (e.g. Environment Agency). Many reviews following the event (e.g. Association of British Insurers, 2007, 2008; Communities & Local Government, 2008) highlight and stress the value of this structure for building informal relationships with those responsible for different assets and services, sharing data and resources, and the value of the joint lessons learned.

3.4. Wildcard events provide opportunities for behavioural change and re-evaluating the provision of infrastructure

Wildcards often force or provide a catalyst for behavioural change at a range of levels from the individual, to communities, to the national and international level. Guiver (2011) describes travel adjustments following the 2009 floods affecting Workington, UK. Severe fluvial flooding destroyed a major road bridge that connected the town centre and the north side of the town, to drive between the two places meant an 18 mile detour on a road that became heavily congested. However, the railway bridge was still operational and a footbridge was quickly built to provide access by foot or bicycle between the two areas. In additional a temporary railway station was established on the north side of the town, buses were rerouted and co-ordinated to pick up and drop off passengers at the footbridge and a temporary supermarket was erected on the north side of the river. Guiver conducted a travel survey of residents of Workington. Results revealed that during and after the closure of the road bridge revealed that people's travel behaviour changed. Fewer trips were taken overall and more were completed using public or more sustainable forms of transport. This case study also highlights that shocks can provide an opportunity to re-evaluate the provision of infrastructure. There were arguably preferable alternatives than the road bridge to connect the two areas of the town that would also contribute to other targets relating to reducing greenhouse gas emissions and promoting healthier lifestyles. A rapid response at the landscape level to relax planning rules that govern the regime that enabled the temporary railway and supermarket to be operational reduced the potential disruption of this event.

The earthquake that hit Japan on 11 March 2011 and the subsequent tsunamis caused widespread infrastructure damage. Entire villages and towns were eradicated, houses and buildings were washed away, roads and railways buckled, power lines were brought down and impacts on major companies affected supply chains globally (Yeh, Sato, & Tajima, 2013). Two million people were without power during the winter conditions and 1.5 million without drinking water (NPR Staff & Wires, 2011). Fujina (2011) states the major focus was on the Fukushima nuclear plants, which reduced power production by 40%. Japan's energy supply is isolated, having no interconnections with neighbouring countries. In the short term, the electricity companies relied on the population reducing their consumption. However, this shock prompted a national review of the country's energy policy and turned public opinion largely against nuclear power i.e. actors causing a disruption in the regime. Japan relies on nuclear for about 30% of its power supply. The last national energy plan, published in June 2010, proposed nine additional nuclear units by 2020 and 14 or more by 2030. These large increases in nuclear capacity were expected to contribute to achieving Japan's ambitious CO_2 emissions-reduction target (25% below 1990 levels by 2020). However, the disruption at the regime level will require a change at the landscape level. This event also stimulated landscape level changes in other counties – Germany permanently shut down eight of its reactors and pledged to close the rest by 2022 (Bohl, Kaufmann, & Stephan, 2013).

4. Use of wildcard event for futures planning

Scenario development is a key methodology in futures research, within which there are many techniques (see Bishop, Hines, & Collins, 2007). Wildcards, by definition as low probability, high impact events are outside the 'probable' realm (Voros, 2003), leading to abrupt changes. Peterson (1999) when considering strategic planning with respect to wild cards asked the following questions: which are the most important wildcards for an organisation; can their arrival be anticipated; and is there anything that can be done about them. Mendonça, Cunha, Kaivo-oja, and Ruff (2004) suggest that if these questions can be answered the impact of some negative events may be minimised. It is incorrect to suggest that wild cards are unimaginable, for example, Cornish (2003) states that the warning signs of an attack like September 11 were there, not least a failed attack in 1993. Hiltunen (2006) provides a review example of wildcards in the literature and concludes that many are in fact gradual changes. Weak signals, which are seen as information on potential change of a system towards an unknown direction have an important role (Ansoff, 1982), that allow a critical reflection of decision-makers and organisations, that leads towards a consideration of implicit assumptions, a reduction of "blind spots" and thus facilitates overcoming mind-sets (Mendonça et al., 2004). Furthermore, Mendonca et al. argue that weak signals must be acted upon. We used a wildcard in the development of a scenario that was 'possible', albeit the period of disruption would have been short, the potential consequences and level of decisions in terms of infrastructure would have been greater. Arguably, as evident from the outcomes listed above, the function of this wildcard was to 'stretch' and 'expand' current thinking as described by Barber (2006). It could be argued that here the use of a wildcard scenario led to the detection of a range of weak signals that could be addressed before they potentially create a more abrupt change.

Wildcard are also used alongside other forecasting tools and methods (see Barber, 2006): Causal Layered Analysis which assesses the depth or quality of discourse of a particular subject; The Foresight Matrix which helps identify strengths between various components, this could have relevance to infrastructure given the increasing degree of interdependencies between various systems; trends i.e. shifts that can be measured and projected – again this approach could be used in the context of infrastructure given the observed changes in demand, quality etc.; Environmental Scanning, gathering as much information as possible to expand the knowledge base – this could lead to other wildcards being discovered; backcasting, which helps understanding how a particular future is formed – this could be useful in the longer term need to plan resilient infrastructure systems to a range of external factors; Transformative Cycle, which is an ongoing process that deals with a change of an outward appearance or inner nature – in the context of infrastructure this could be privatisation of an asset or the introduction of a new regulation or legislation.

The most common purpose of wildcard events is within scenarios development and to enable the consideration of alternative futures (Barber, 2006). Following the methodological approach and analysis described above, the lessons learned regarding the value of wildcard events were used to design a series of workshops in a 'Decision Theatre' setting (Walsh et al., 2013). Such events allow decision-makers to critically reflect upon potential outcomes of a range of models or scenarios (Mendonça et al., 2004; Steinmueller, 2011). The first two workshops took place with a range of stakeholders from key infrastructure and service providers. The first event aimed to explore the current vulnerabilities of the city to an extreme storm event, a 1 in 100 year storm event scenario developed, drawing conditions and evidence from past events. A series of visualisation screens were used to present the narrative of the storm conditions, the impacts as they occurred throughout the scenario at a range of scales, displayed on maps and a series of interactive buttons that enabled different layers of information, for example locations of key assets and network. The scenario of both strong winds and intense rainfall, which caused extensive pluvial flooding severely affected and disrupted transport infrastructure and services, power supply, schools, hospitals, residential and commercial properties, and began to explore the inter-connected nature of these systems and long-term implications of decisions made by relevant organisations. A second event, with similar stakeholders focussed on adaptation solutions to wildcard flood events. Again participants were able to interact with the information and modelled scenarios to investigate a range of policy options that could help alleviate surface water flooding in the city centre. Both events were framed in the context of future planning in the face of climate change, new infrastructure developments and a changing demographic.

The design of the workshops was similar to that of the Delphi technique (Linstone & Turoff, 1975) whereby a scenario was used to facilitate a group conversation amongst experts around a complex issue. However, the key design and function was not as rigorous as a tradition Delphi approach. For instance, the discussion was entirely open, as opposed to individuals considering questions from their area of expertise; this on turn meant there was no controlled feedback. This may have resulted in a bias in the conversation and the dominance of certain issues from more vocal participants; anonymous comments common with the Delphi procedure may have been more valuable. Following a stakeholder mapping exercise, experts were targeted to participate in these workshops to cover all major infrastructures and services in the city. However, it is recognised that based on the actual participants that some areas of infrastructure system of the city were not represented.

These two events had many positive outcomes which could lead to better planning solutions to help the city become more resilient to climate-related events:

- Identification of key datasets that would enhance the relevance, reality and impact of the wildcard event scenario that would mean it was also more valuable to share among different organisations, such organisations were identified. This could be iterative following actual events by feeding in real data.
- Recognition of the value for improved system understanding and trajectory of future planning developments and decisions of sharing, collating and visualising datasets from a range of organisations on a transferable platform.
- An agreement between different organisations and providers emerged to share datasets and other models to improve understanding of the physical and social vulnerabilities associated with surface water flooding in the city.
- Discussion and comparison of a range of adaptation options. This included identification of their multiple benefits (e.g. increasing green space helps alleviate increasing temperatures and enhances its value for ecology and well-being) and the important debate regarding who pays for adaptation and the case for new business models for future planning of such assets.
- Identification that more research is needed on the secondary and indirect potential impacts of flooding i.e. cost to public and private assets and infrastructure. It was further recognised the importance of considering climate risks in city-wide development plans and identified which areas of the city may benefit from monitoring to improve understanding risks.

Subsequently, a combination of the two events was presented at a further two events with members of the public. The timing of these events was quite fortuitous in that they took place after an extreme pluvial flood event in the city which affect and disrupted infrastructure services, as well as residential properties. Here, the scenario combined with the actual disruption to people's lives affected their personal choices and resulted in them being more susceptible to changes that they could personally make over the long term to reduce their vulnerability to flood risk. The combination of the scenario and a personal perspective and realism that the participants had meant this technique was more impactful and led to a greater level of learning.

Developing a scenario for a particular place that was based upon a wildcard event was advantageous in engaging all infrastructure providers and related services within an urban system. Outcomes from the event certainly marry-up with known strengths of scenario techniques. Whereas the scenario was fixed ahead of the event, it led to conversations about alternative developments i.e. more than one possible outcomes and a series of 'what-if' questions and unimaginable possibilities. As described above the scenario highlighted weak signals and how they could be used in longer term planning and improved communication and a shared ownership of the issues amongst the organisations involved. The method also has a number of weaknesses which means it not may always be suitable for other situations or cultural contexts. The process is time consuming in terms of data collection and interpretation, and given the qualitative approach, more emphasis needs to be given to selection of participants who have a deep knowledge of their area (Mietzner & Reger, 2005).

5. Conclusions and future directions

In this paper, it is argued that infrastructure systems are inherently socio-technical systems and should be analysed as such. In this complex field, new methodologies are required which integrate engineering and social science thinking and approaches to envisage powerful means of reduction required to create transition to a more integrated, resilient or even less infrastructure system. Furthermore, innovative processes are required which engage multiple stakeholders with envisioning more sustainable future infrastructure configurations and co-designing the transition towards their (de) construction. In this paper, the wildcard events are used as mechanisms for gaining understanding of infrastructure systems by a method of 'destructive testing', a method traditionally used by engineers to gain an understanding of material components and simple engineering mechanisms. The social science methodology of MLP is used to analyse these 'broken' systems for a socio-technical perspective and the results utilised to designing a co-design methodology.

This paper proposes that wildcard events can be moments of great learning and an opportunity to improve infrastructure. This paper considers how to embrace such events to infrastructure systems as opportunities for higher level learning to consider the necessary infrastructure transformation required for the coming decades. These events highlight the obvious challenges that infrastructure systems currently (and more so in the future) will need to tackle. Over the longer term, it is not just wildcard events that are of relevance to infrastructure systems but a range of what may be described as 'weak signals' are also prevalent (Saritas & Nugroho, 2012; Saritas & Smith, 2011). Whereas here we have focused on wildcard events on infrastructure systems i.e. risks from extreme weather, natural disasters and terrorism, using weak signals as a tool to help avoid and plan for other prevalent vulnerabilities: interdependencies between infrastructure systems, ageing infrastructure, reduced public spending, private ownership of assets, financing of projects, is equally as important for complex infrastructure systems. Projections of climate change, economic growth, population growth and urbanisation require urgent attention, as do understanding and consideration in the future planning of infrastructure. The wildcard examples described in this paper demonstrate that they can open up impactful intervention points such as: disrupting the regime, providing a catalyst for niche innovations and inducing changes at the landscape level; providing an opportunity for learning both within and across different infrastructures and across geographical regions; improving relationships and procedures between different infrastructures to promote the move away from systems being managed in silos towards a more integrative approach and providing an opportunity for individuals, a range of organisations – managers and providers of infrastructure both nationally and internationally, to evaluate the provision of infrastructure and induce behavioural change.

Most particularly, this paper contends that part of our long-term adaptation strategy for infrastructure should consider the possibility of 'less' in order to promote more sustainable behaviours. Wildcards by definition as low probability, high impact events are outside the 'probable' realm (Voros, 2003), leading to abrupt changes. Wildcard events are considered as one of the very few mechanisms available to achieve less due to the inherent obduracy of the built environment, by restoring it to a better state after the event, rather than re-instating it to what it was prior to the event. However, one particular point in the report by the UK, the Council for Science and Technology (2009), that there is 'no overall vision' needs to be redressed urgently with the idea of considering the possibility of less in order for the power of wildcards to be capitalised upon. The scale of the event i.e. the life-cycle (Steinmueller, 2011) and the scope of the long term planning opportunity need to align; an immediate response to a small event may be less likely to result in more sustainable changes. We have shown that a wildcard event is a moment, or 'window of opportunity' in which users and operators come together across infrastructures to make decisions and to assess needs. Furthermore, we have demonstrated how a wildcard scenario event can be valuable in encouraging cross-sectoral discussions and analysis of long-term planning decisions and in changing behaviour of those who have lived through such wild-card events. The sort of revaluation that is engendered by the experience of wildcards is what is required to make the necessary changes to shift existing paradigms, thoughts and behaviours leading to the ideal of sustainable infrastructure for 2100. There is, therefore a need for the consideration of the possibility that a reduced infrastructure might be an option, to produce a vision of what a reduced infrastructure might look like, and a governance structure which can capture the great opportunity which wildcards present.

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