Looking through the lens of Nature: can we think of infrastructure systems as an extension of natural systems?

Shima Beigi[1],*

Colin. A. Taylor[2]

Abstract

Following recent extreme events in New Zealand, Haiti, and Japan, and other parts of the world, infrastructure systems have copiously been identified as lifelines of cities and essential to the smooth functioning of modern societies (1). Therefore, resilience of these systems cannot be defined based on mere infrastructure's physical attributes (2). Rather resilience can best be considered as an interactive process that unfolds over time and which is continuously influenced by ongoing change in the context (3). In other words, maintaining resilience of complex and critical infrastructure systems as a whole including social systems, organisational, technical, and economical systems (4) should become an essential, continuous, and engineered part of their management (5).

An Overview of complex adaptive system

In the current state of social and ecological resilience research, it is often said that complex social systems are a sub-system of nonlinear complex adaptive systems that contain system-level oxymoron properties such as resilience, adaptability, evolveability, and stability (6). Complex adaptive systems are open systems composed of many interacting components that through interacting with their surroundings both autonomously and in interaction with their environment change, self-organise (7, 8) toward a state of equilibrium or attractors, and give rise to emergent properties (9) such as mutual adaptation of genes give rise to differentiation of tissues and emergence of different organs that cannot be found in individual parts (10).

The process of self-organisation is typically takes place in nonlinear systems, which are far from their thermodynamic equilibrium state. Nevertheless, nonlinear systems generally have several attractors. When a system resides in between attractors, it will be in general a chance variation, called *fluctuation* in thermodynamics that will push it either into the one or into the other of the attractors (11). Given this notion, it can be conjectured that the behaviour of the system will move towards attractors.

Some attractors will embody our notion of desired states and can be called good attractors or good patches (12), whereas other attractors might take us too undesired states or what here is called bad attractors. Appearance of alternative states introduce interesting element: the possibility of path-dependent phenomena (13). In these cases, relevant to both biological and technological evolution, the initial conditions play a key role. Small differences in the initial state can actually lead to very different outcomes, thus introducing the role for history. By tracking the history of life and society, when a given parameter is tuned and crossed a threshold we can observe change in system organisations or dynamics.

* Author to whom correspondence should be addressed: Dr. Shima Beigi. Shima.beigi@bristol.ac.uk

[1],[2] University of Bristol, University Walk, Queen's Road, Faculty of Engineering, Department of Civil Engineering, Bristol, BS8 1TR

These different patterns of organisations have been termed as '*Phases'* that contains evidence of deep changes in 'life forms', ecosystems, and civilisations.

A modern society as a complex adaptive system has been self-organised by the act of human intervention toward creating desired aggregation of *potential attractors* namely cities. However, to enable these process of self-organisations, having an access to multiple sub-systems and pathways of flow of resources across the entire body of cities, communities, and individuals is necessary.

Resilience of infrastructures as network of energies can consequently be seen as an emergent, desirable, complex, and adaptive property. Therefore, similar to description of emergent properties in CAS; resilience emerges from spontaneous dynamics of local and sub-processes interaction in their continual mutual adaptations to a changing environment. The role of flow of resources in directing resilience in complex systems can be seen after massive changes that have enough potential energy to shift/ flip the entire *system* into a completely novel chapter of performance.

In the 2011 Tohoku earthquake in Japan, the widespread devastation was all too evident from the cascade of media images, now supplemented by objective field studies of the actual impacts. These images reveal how the earthquake and tsunami damage disrupted, and in some cases totally eliminated, the resource networks on which the Japanese and global society depends - indeed, one of the primary purposes of the society is to create and maintain these sustaining resource networks.

From this perspective, a resilient recovery process is the process of purposeful *rebuilding* and *reinstatement* of these *resource networks* in order *to enable the society to attain its restated goals*. These goals might be simply to return to the society's state or condition to that which existed prior to the event, or the experience of the event might cause society to reflect and decide that it *wants/ prefers* to move towards a new, less vulnerable and more sustainable state.

The choice of development trajectory and its pace and the actions necessary to achieve the desired development, emerge from the complex interactions of the societal system and its constituent actors (14). Thus, it is argued that resilience is an emergent property of the complex adaptive societal system (15), of which physical infrastructure is just a part.

In responding to an event like Tohoku, a society must deploy its *full inventory of resourcefulness*. The actual conditions arising from the event cannot be known until the event has happened. Thus, the first component of the resourcefulness inventory to be deployed must be the ability to observe and understand what has happened. This societal learning and reflection have to work simultaneously and coherently across the spatial scales - from the detailed, highly localised, knowledge of the householders watching their homes being washed away, to the sophisticated, coarser scale, real-time pictures being presented to national and regional governments.

Previous scenario speculations can help to structure and focus this learning, and to develop effective enabling tools, but the uniqueness of the actual event means that the actual learning can only happen after the event. Having made sense of the actuality of the event, the society then needs rapidly to decide what chain of future states it want to move through, and over what time scales, it needs clarity of its society purpose, goals and vision. Then the society needs to design and implement the actions needed for it to attain these states. These actions are fundamentally a matter of restoring the society's sustaining resource networks and associated resource flows (16).

Such restoration depends on the availability of many other components of the resourcefulness inventory including know how, materials, equipment, people, governance, learning, decision making, confidence (17). Thus, '*the degree of resilience depends on the degree of resourcefulness*'. If a society is to be resilient, it needs to focus on developing its fundamental resourcefulness with the goal of ensuring that it has overwhelming resourcefulness sufficient to enable it to cope with any eventuality. Figure 1 illustrates the concept of resourcefulness and its impact on subsequent positioning of system in the vulnerability continuum (18).

The concept of vulnerability continuum (Fig. 2) is adapted from (19) and is linked to the role of investment and enhancing resourcefulness of complex adaptive systems in directing systems, managing the level of exposure to stressing condition, and steering the trajectory of adaptation toward resilient thresholds.

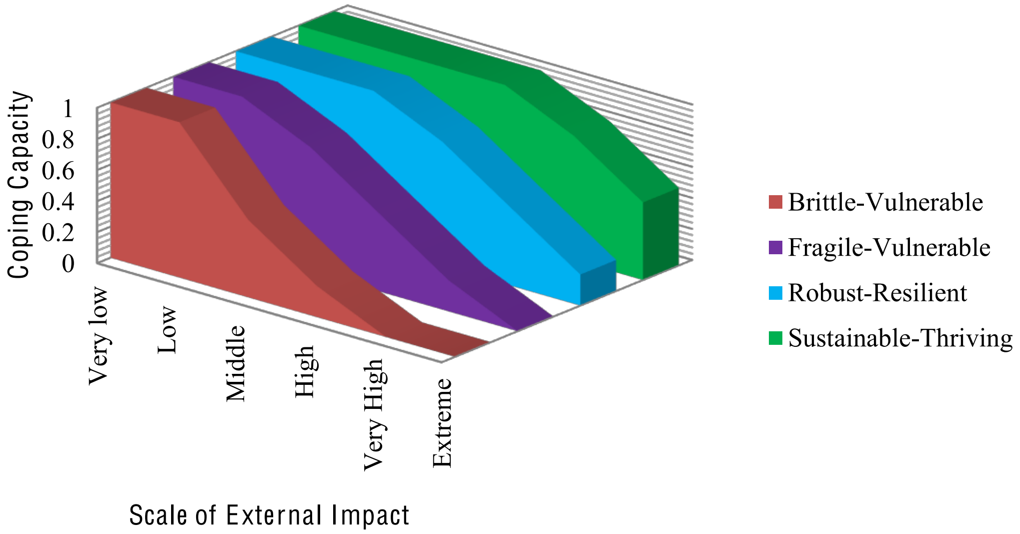

Figure 1. Different Location of the Social Agents on the Resilience Vulnerability Continuum (Beigi 2014).

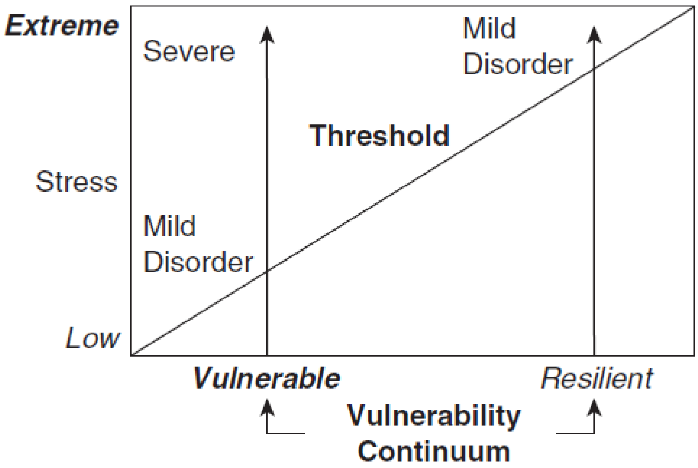

Figure 2. The Role of Predisposition of System in Response to Stress Ingram (2005).

In other words, *positive manifestation of resilience at global scale* (20) in the face of changing condition is highly dependent on resourcefulness of underlying mechanisms (21) in creating coherent and synergetic operational workspaces, knitted together with a shared-vision, and operational rationales across the system a whole (22).

These underlying mechanisms are themselves dependent on a constant flow of resources of different kinds to continue to operate in an acceptable state and support sustainability of desired states in the system as a whole.

Consequently, the fundamental essence of resilience as the ability of system to cope with changing condition and continue to flourish and maintain a positive and relatively stable state is interdependent with accessibility of underling processes to sufficient amount of necessary resources (23, 24) to continue to function toward desirable or enhanced states (25, 26).

The functionality of super process of resilience and its intricate dependence on constant flow of different types of resources in the abovementioned scenario, shares similarities to the process of survival of the fittest, fitness landscape, resilience of ecological systems and the evolution of process of life in the biological realm. The process of survival of the fittest and robustness of life across diverse ranges of life domains in a broad sense is also dependent on: a) constant inflow of energy and materials into organisms as open and dissipative systems and b) on organisms' abilities to strategically adapt to the changing condition (27), remain productive and evolvable.

From this point of view, cities as an intensification of human interaction made possible by connection of energy flows across space and time (28) regulate their metabolic pathways through constant flows of diverse forms of energy and materials and constantly feeding back energy to the other components. Through this dynamic and continues process of energy acquisition, transformation, dislocation, and dissipation matter condenses and creates 'storages' of different kinds (29, 30).

The quality and quantity of these storages are thus direct function of ability of 'energy carriers' in the system of cities as whole including ability of their inhabitants and their built infrastructures in *capturing* and *attracting* flows of energy, *transforming* them into higher/different forms, feeding back and forward energy and material into different parts of the system and mobilising resources to the other parts of the whole in order to ensure various groups of stakeholders are enabled to have access to uninterrupted flow of energy and resources most of the times.

These stakeholders can be thought of different group/ types of storages and enabling resources and processes, which not only consume resources but also, feedback resources to the other parts of the system. Considering stakeholders as storages of resource and energy shows that the ability of different groups of people from different parts of the system and with different degree of resourcefulness influences the way in which the trajectory of responsiveness of system unfolds.

This means that information related to self-organisation processes of complex infrastructure systems, similar to the patchy nature of ecological systems, is not predefined explicitly in any participated parts, rather the process of emergence is always novel and unique because it is constantly being resourced from the dynamic interaction of system players taking shape by them which will become embodied in the collective mind of the system.

City Resilience

A city and its supporting infrastructure systems therefore can be considered as continuation of natural systems, being made by aggregations of human will and desire. It is as though humans across the world have taken the process of evolution of life into a different level of manifestation. However, from biological perspective cities are similar to and differ from ecological systems (31).

Therefore, they are resilient if their infrastructure systems are resilient in a sense that is able to remain bounded or remain close enough to a set of desirable state or the attractor around which the system prefers to remain in time of perturbations by utilising rapid support of feedback loops and maintain their functionality while being able to continue to empower system's reorganisation processes. Nevertheless, not all form of energy is of the same value and from the same kind of quality because various factors contribute to the ability of flow of energies to do "useful work" and enable complex adaptive systems to continue to thrive in the face of adversity. These factors including convertibility, flexibility, concentration, and ease of transformation, are linked to the diverse ranges of transformability of infrastructure systems as enabling resources to influence degree of resiliency and resourcefulness of users.

A resilient city needs sources of energy and enabling processes in order to respond to an external action and move toward a better state. The sources of energy must also be delivered in sufficient and pertinent amount of energy and at a sufficient rate to the whole structure of the system or in the area of responsibility i.e., right place.

This concept of right amount and right type of energy, right timing, and right place means that a resilient system needs to act fit, think fit, move fit or what this research calls dynamic resourcefulness. The nature of dynamic resourcefulness can be elucidated with a simple example from natural systems.

The process of resource acquisition and nutrient transformation in a forest as a whole is enabled by both the collective processes of its internal infrastructure systems including the system of roots supported by the network of rhizomes that are capable of multidimensional expansion in the soil fitness land-scape and amplifying other parts of the tree by reaching unique regions of the soil-scape, the system of leaves combined with supporting energy capturing systems, tree trunk and its unique physical attributes, and etc. in maintaining a dynamically stable yet adaptive, robust yet evolvable, and redundant platform for the system of the hypothetical forest as whole and enabling it to cope with the changes of its internal and external environment such as changes in the amount and magnitude of sunlight, flow of water coming from internal structures as well as external sources such as precipitation, architectural properties of soil infrastructure system, the frequencies of fire and dynamics of outbreaks, degree of invasion by other species or existence of available potential space for change.

Therefore changes in the behaviour of system of forest can be tracked by means of detecting changes in the characteristics of inflows and outflows, and stocks or inventories of energy and materials. What goes into the forest and what goes out of it with respect to previous states of interactions provide ecosystem managers and ecological engineers with a sense of system's natural tempo of evolution. Therefore, stocks of energy and materials create a form of memory for the system that act nonlinearly as inventory lists or storages for each individual sub-system in the system of forest and are fundamental sources of change in multidimensional and multilevel directions.

The navigation of resources and self-organisation of natural systems in respond to changing condition are dependent on dynamics of feedback loops, cross-scale dynamics, their trade-offs with their surroundings, time profile of change, architectural properties including structural integrity, combination or embellishment of resources of ecological systems, and degeneracy (32) that ensure resilience and continuity of key functioning processes and services and will resource robustness to grow over evolutionary time (33). Put it differently, the ability of ecosystem to utilise available resources by means of its redundancy and complexity and adapt to disturbance by utilising its buffered stability depends on the storages and interactions within an ecosystem (34) that enhance flow of available information (35).

Similar to the system of a forest, a city for its functionality and providing a buoyant mode for social communities is dependent on a constant flow of resources (36) . However, humans are equipped with the most advanced type of control mechanism across the domain of life whose internal dynamics give rise to emergence of a sophisticated level of mental faculty and cognition that enable them to consciously and purposefully modify; exert deliberate influences on its surroundings, and create, destruct, or trigger emergence of new attractors across different regions of shared landscape of performance and binds energy, time and space simultaneously (37).

Through these influences, humans are therefore able to '*design and architect'* their own tools from previous forms of resources building infrastructure systems from diverse ranges of natural resources, 'create' new types of resources in different quality and quantity, and 'learn' valuable insights from his previous experience of using resources.

The combination of these processes of designing, creating, and learning enhances humans accessibility to resources or increase his resourcefulness, their adaptive capacity' boundaries and consequently their degree of resiliency in the face of the unknowns. Resilience in this context is a super process is linked to the linking processes of a set of adaptive capacities to a positive trajectory or trajectories of functioning and adaptation after a disturbance to the current desirable state (38).In this context resilience is not equated with the outcome, but rather with the process linking resources or enabling adaptive capacities to outcomes or desired attractors such as the dynamic state of positive adaptation for human individuals and communities as a whole. The processes of positive adaptations in social systems are collectively manifest in wellness of communities.

Therefore an integrated framework can provide a robust basis for investment in a resilient set of services that will improve the serviceability of system as a whole. This research by using the concept of resource flow analysis concludes that enhancing ability of systems to make a prediction of how often extreme condition occur and what is the uncertainty in the detail of such predictions, and increasing intrinsic resilience of the services and systems to wide ranges of manifestation of change and not solely extreme events across the whole system boundaries, maintains a tolerable level of loss for communities (39) , and entrain the trajectories of dynamic resourcefulness in infrastructure systems toward globally green, sustainable, and resilient states.

Conclusion

Three fundamental building blocks of the newly emerging theory of Mindfulness Engineering are identifies as the following:

1) ***Infrastructure systems are expansion of natural systems.***

Infrastructure systems are compact spaces made by man and from natural resources and are concrete manifestation his abstract needs. For instance, the emergence of an infrastructure system such as water networks is provided by existence of a triggering point, which is the need to have an access to a clean source of water as well as mobilise this accessibility to different parts of a city.

In short, infrastructure systems are both means and ends that 'entrain' and 'empower' self-organise-abilities of communities around their desired states across various scales in space and time. A globally resilient system is not only capable of coping with environmental perturbations but also, is able to focus its inventories of resourcefulness collectively to shape the landscape and its basins, create better attractors, transform resilience from the domain of possibilities and planning to the actual arena of action and subsequently evolve itself systematically.

2) ***To build resilient nations, we need to move beyond artefact centric view of critical infrastructure systems toward 'service-centric or resource-centric' view of complex adaptive infrastructure systems.***

The outcome of such shift consequently changes the process of asset management and the process of evaluation of these essential systems. It also has the potential to encourage different users of complex adaptive infrastructure systems to purposefully assign a price or value for resilience (40) in their processes of resource acquisition, transformation, mobilisation, and dissipation, harmonise the balance between demand side of the system and the consumption side (41) ,and register to the notion of end-to-end resilience. In a nutshell, the value of an asset in the framework of dynamic resourcefulness is not only linked to its physical attributes but also, to its critical role in maintaining and supporting resilience of modern social system as a sub-system of nonlinear complex adaptive systems.

3) ***Different degrees of resourcefulness give rise to different morphologies and typologies of resilience in different systems.***

In complex adaptive systems that have multiple interacting agents, we essentially have different resource inventories. Different stakeholders therefore can bring various trajectories with different views of resilience with themselves in forms of diverse types of mental models with diverse system of values and needs into their reciprocal states and create pulses of change in other and sometimes remote areas in the shared landscape of performance.

These different views of resilience bring about alternatives for system stakeholders across the system and a source of change either positive or negative (42) which their outcomes can be used to steer toward fitter basins of attractions. By tracking how changes in the flow of energies influences system behaviour and its preferences, system developers can gain insight about designing globally resilient systems.

A resilient system must be able to act on these different levels of resourcefulness to be able to maintain the diversity meaning that the amount of choices that a system can make is highly linked to its degree of resourcefulness and consistency of these resources. For instance, a complex adaptive infrastructure system is essentially a part of cognitive map of social systems.

An infrastructure's integrity is maintained by users in that an infrastructure like technological systems also 'wants' resources (43) to fulfil the objectives of itself and its users. This means that a bi-directional and synergetic relationship between users of infrastructure systems and infrastructure systems as a whole does exist which might be considered as an advanced version of logical interdependencies suggested. In other words, it can be said that a complex infrastructure system is essentially a part of cognitive map of social systems.

If users of an infrastructure have a reductionist mental model of the system of which they are part, and from which they benefit, the system cannot be categorised into higher typology and morphology of resilience. Therefore, an increase in resilience of system in one part of the systems does not mean that the system as a whole have achieved an enhanced degree of resiliency. Moreover, the process of human development is a multidimensional and multidirectional process. This means that to manage for thriving systems, control, and flexibility of self-organisation need to be linked. This is achievable if the role of diversity of different perspectives and components in the system is considered as a useful resource that can support structural integrity and persistence of key functions and relationships in the system in time of shock trigger novelty, and evolution needs to be incorporated in systematic analysis of resilience of complex adaptive systems.

Acknowledgments

This working article is an ongoing part of the research on resilience of complex adaptive social, ecological, psychological, and technical systems that is conducted by the authors at the University of Bristol, faculty of engineering, department of civil engineering. The authors would like to thank Free University of Brussels, The Global Brain Institute, Professor Francis Heylighen, the Engineering Physics Science Research Council, and the International Centre for Infrastructure Futures.

References

1. Adachi, T. and B.R. Ellingwood, *Serviceability of earthquake-damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability.* Reliability Engineering & System Safety, 2008. **93**(1): p. 78-88.
2. Sheffi, Y., *Supply Chain Strategies: Building a Resilient Supply Chain* Harvard Business Review, 2005. **1**(8): p. 1-14.
3. Gladstone, A., *What supports adults to return to learning* in *Improving Your Reflective Practice Through Stories of Practitioner Research*. 2012, Routledge Abingdon
4. Bruneau, M., et al., *A framework to quantitatively assess and enhance the seismic resilience of communities.* Earthquake Spectra, 2003. **19**(4): p. 733-752.
5. Hudson, S., et al., *Engineering resilient infrastructure.* Proceedings of the Institution of Civil Engineers-Civil Engineering, 2012. **165**(6): p. 5-12.
6. Walker, B., et al., *Resilience, adaptability and transformability in social-ecological systems.* Ecology and Society, 2004. **9**(2).
7. Heylighen, F., *Complexity and Self-Organisation* Taylor & Francis 2008: p. 20.
8. Levin, S.A., *Self-organization and the emergence of complexity in ecological systems.* Bioscience, 2005. **55**(12): p. 1075-1079.
9. Goldstein, J., *Emergence as a Construct: History and Issues.* Emergence, 1999. **1**(1): p. 49-72.
10. Gershenson, C. and F. Heylighen, *When can we call a system self-organizing?* Advances in Artificial Life, Proceedings, 2003. **2801**: p. 606-614.
11. Heylighen, F., *The Science of Self-Organisation and Adaptivity* in *Knowledge Management, Organizational Intelligence and Learning, and Complexity, in: The Encyclopedia of Life Support Systems, EOLSS*. 1999, Publishers Co. Ltd: Belgium. p. 253--280.
12. Dai, L., et al., *Generic Indicators for Loss of Resilience Before a Tipping Point Leading to Population Collapse.* Science, 2012. **336**(6085): p. 1175-1177.
13. Sole, R.V., *Bifurcation and Catastrophes* in *Phase Transitions* 2011, Princeton University Press New Jersey
14. McDaniels, T., et al., *Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation.* Global Environmental Change-Human and Policy Dimensions, 2008. **18**(2): p. 310-318.
15. Folke, C., *Resilience: The emergence of a perspective for social-ecological systems analyses.* Global Environmental Change-Human and Policy Dimensions, 2006. **16**(3): p. 253-267.
16. Adger, W.N., et al., *Social-ecological resilience to coastal disasters.* Science, 2005. **309**(5737): p. 1036-1039.
17. Adger, W.N., *Social and ecological resilience: are they related?* Progress in Human Geography 2000. **24**(3): p. 347–364.
18. Beigi, S., *Mindfulness Engineering: A unifying theory of resilience for the volatile, uncertain, complex and ambiguous (VUCA) world* in *Civil Engineering*. 2014, University of Bristol. p. 342.
19. Ingram, R.E. and D.D. Luxton. *Vulnerability-Stress Models*. 2005 [cited 2012; Available from: http://www.sagepub.com/upm-data/5348_Hankin_Final_pdf_Chapter_2.pdf.
20. Masten, A.S., *Resilience in Individual Development: Successful Adaptation Despite Risk and Adversity* in *Educational resilience in inner-city America: challenges and prospects*. 1994, Lawrence Erlbaum Associates p. 3-10
21. Masten, A.S. and J. Obradovic, *Disaster Preparation and Recovery: Lessons from Research on Resilience in Human Development.* Ecology and Society, 2008. **13**(1).
22. Petak, W.J., *Earthquake resilience through mitigation: a system approach.* International Institute for Applied Systems Analysis, 2002.
23. Adger, W.N., *Vulnerability.* Global Environmental Change-Human and Policy Dimensions, 2006. **16**(3): p. 268-281.
24. Bonanno, G.A., *Loss, Trauma, and Human Resilience: Have We Underestimated the Human Capacity to Thrive After Extremely Aversive Events? .* Psychological Trauma: Theory, Research, Practice, and Policy, 2008. **S**(1): p. 101–113.
25. Brooks, N., W.N. Adger, and P.M. Kelly, *The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation.* Global Environmental Change-Human and Policy Dimensions, 2005. **15**(2): p. 151-163.

26. Allison, E.H., et al., *Vulnerability of national economies to the impacts of climate change on fisheries.* Fish and Fisheries, 2009. **10**(2): p. 173-196.
27. Provenza, F.D., et al., *Self-organization of foraging behaviour: From simplicity to complexity without goals.* Nutrition Research Reviews, 1998. **11**(2): p. 199-222.
28. Hackney, W.S.a.L., *Energetic Organizations: Frameworks for Urban Flow and Form*, in *FLUX Sherman* 2010, University of Virgina USA. p. 8.
29. Brown, M.T., H.T. Odum, and S.E. Jorgensen, *Energy hierarchy and transformity in the universe.* Ecological Modelling, 2004. **178**(1-2): p. 17-28.
30. Odum, H.T. and E.C. Odum, *Modelling for All Scales* An Introduction to System Simulation 2000, San Diego, California Academic Press 445.
31. Bettencourt, L.M.A., et al., *Growth, innovation, scaling, and the pace of life in cities.* Proceedings of the National Academy of Sciences of the United States of America, 2007. **104**(17): p. 7301-7306.
32. Whitacre, J.M., *Degeneracy: a link between evolvability, robustness and complexity in biological systems.* Theoretical Biology and Medical Modelling, 2010. **7**.
33. Edelman, G.M. and J.A. Gally, *Degeneracy and complexity in biological systems.* Proceedings of the National Academy of Sciences of the United States of America, 2001. **98**(24): p. 13763-13768.
34. Odum, E.P., *Strategy of Ecosystem Development.* Science, 1969. **164**(3877): p. 262-&.
35. Ulanowicz, R.E., *Complexity, Stability and Self-Organization in Natural Communities.* Oecologia, 1979. **43**(3): p. 295-298.
36. Andrew, R., *Building community resilience.* Proceedings of the Institution of Civil Engineers-Civil Engineering, 2012. **165**(6): p. 59-64.
37. Korzybski, A., *Manhood of Humanity* The Science and Art of: HUMAN ENGINEERING. 1921, NEW YORK: E.P Dutton & Company
38. Cutter, S.L., C.G. Burton, and C.T. Emrich, *Disaster Resilience Indicators for Benchmarking Baseline Conditions.* Journal of Homeland Security and Emergency Management, 2010. **7**(1).
39. Mileti, D.S., *Disasters by design.* Facing Our Future: Hurricane Floyd and Recovery in the Coastal Plain, 2001: p. 127-139.
40. Collins, B., *Transport Services and Systems, Resilience and Investment.* Department for transport, UK., 2011
41. Amin, S.M., *Enabling a Resilient and Secure NorthAmerican Electric PowerGrid*, in *The 4th International Symposium on Resilient Control Systems*. 2011, University of Minnesota: USA.
42. Walker, B.H., et al., *Drivers, "Slow" Variables, "Fast" Variables, Shocks, and Resilience.* Ecology and Society, 2012. **17**(3): p. 4.
43. Kelly, K., *What Technology Wants* 2007, New York, USA: Viking 416.