Resilience Potential, Robustness, and Edge of Collapse
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Abstract
Despite a body of work investigating different types of resilience in the contexts of engineering, ecology, disaster risk reduction and social science, there is no simple way of enumerating resilience in these contexts. This working paper attempts to establish such enumeration, and it additionally positions the concept of resilience in the context of robustness and edge of collapse.

Keywords: Resilience, Robustness, Edge of collapse

Introduction

The purpose of this working paper is to enumerate the concept of resilience potential, robustness and edge of collapse, in order to facilitate strategic planning of urban and societal futures.

Our overview of resilience will focus across domains of ecology, engineering, disaster risk reduction, and social sciences. In the ecological context, Holling defines resilience as a "measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationship between populations or state variables" (Holling, 1973). Ecological systems are characterised by multiple equilibrium states, and resilience is characterised by thresholds of transition from one equilibrium state to another (Pendall et al., 2010). As these multiple equilibrium states are the signature of dissipative, complex, and essentially constantly changing non-equilibrium systems, resilience is the means of exploration of opportunities for bounce-forward transformations. Thus, Adger (Adger, 2005) defines resilience in social-ecological systems as "the capacity of linked social-ecological systems to absorb recurrent disturbances such as hurricanes or floods so as to retain essential structures, processes, and feedback". In this context, consequences of natural and environmental disasters are considered to be opportunities for innovation (Folke, 2006). Engineering resilience, as defined by Holling (Holling, 1996), is the capacity of the system to regain initial equilibrium. This bounce-back resilience is more associated with existing static structures such as buildings, and it does not extend to multiple equilibrium states associated with ecological and social systems. Jankovic studied resilience of the built environment in the context of extreme weather (Jankovic, 2018) and found that a common denominator between the contexts of a building, a site and a region is a degree of redundancy or spare capacity in the system. Caputo and co-workers proposed acceptance of change in urban planning practice, recognising the ecological resilience as a pre-requisite for urban adaptation (Caputo et al., 2015). Disaster risk reduction resilience has similarities with engineering resilience, including a single equilibrium and bounce-back recovery from perturbation. In this context, Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) was established by the United Nations Office for Disaster Risk Reduction, covering the timescale of 2015-2030, with global targets for substantial reduction of disaster mortality, number of affected people, economic loss, and disaster damage to critical infrastructure. Resilience in the social sciences deals with response and adaptation of individuals and communities to environmental and natural hazards and risks. Thus, Kaswan (2013) introduced 'Seven Principles for Equitable Adaptation', addressing disparity of climate change impacts respective to social inequality, where bouncing-back to status quo is not a viable option for the poor would just re-instate the initial vulnerability (Sampson et al., 2013).

Despite the extensive body of above work and attempts to measure individual aspects of resilience in specific contexts, such as dealing with resilience to floods (Liao, 2012); resilience in the context of risk and environmental sustainability (Coaffee, 2008); and disaster resilience indicators (Cutter

et al., 2010), no simple specification exists for enumerating resilience. This paper will therefore attempt to define resilience using a formula that can be applied to a wide range of cases.

Method

We start the analysis by using the concept of the shortest computer program and will subsequently develop a formula for general enumeration of these concepts. The shortest computer program is a program that carries out a certain task and nothing else. It arises from the work by Russian mathematician Andrey Kolmogorov and is referred to as Kolmogorov Complexity (Li & Vitányi, 1990). Computer programs at the execution level consist of binary code, or strings of ones and zeros. Thus, if a computer program consists of a repeating pattern of 100100100, such pattern may be replaced by 11100, where 11 before 100, corresponding to decimal number 3 in binary notation, is an instruction to repeat the binary digits 100 three times. By replacing the string 100100100 with the string 11100 we have compressed the initial program and made it shorter. If no further compression can be made and the program still carries out the intended task, then such program is the shortest computer program. If a single bit is changed in the shortest computer program, the program will no longer work. Thus, changing 11100 into 11101 will no longer carry out the intended task, and thus running such program will make it crash. We can therefore say that the shortest computer program is the edge of collapse, as changes in its binary code will make the program incapable of carrying out the intended task.

If a single bit in the initial program is changed from 100100100 to 100100101, the program will still have the ability to execute the instruction 100 two times. Thus, making certain changes in a system without affecting the ability of that system to perform intended tasks will make such system robust. Robustness will only be made possible if there are surplus structures in the system that can take a hit without having a catastrophic effect on the system. These surplus structures, such as the repeating structure of the bit string 100, represent a built-in redundancy/spare capacity, which will ensure the robustness of the system.

If the initial program, changed from 100100100 to 100100101, can recover back to the initial configuration 100100100 by some means, we can say that such program is resilient. Thus, the more redundancy/spare capacity in the system, the more chance for the system to recover. A degree of redundancy/spare capacity in the system will therefore not only make a system robust but it will also increase its resilience potential. The difference between resilience and resilience potential in the ability of the changed bits to reset back to the initial values, instead of just having the potential for such reset embodied in the redundancy/spare capacity of the system. In a wider context, instead of a reset to the initial condition, the system can find a new equilibrium state, such as in ecological systems.

We can now summarise these concepts before moving on to a more general enumeration. Thus, the edge of collapse is determined by a boundary or a threshold beyond which the system will not be capable of performing a task for which it has been designed. System robustness is determined by the extent of changes that can be made to the system without causing a detrimental effect on the system's ability to perform a task for which it has been designed. Thus, a redundancy/spare capacity within the system makes the system robust. System resilience potential is determined by the redundancy/spare capacity that is also capable of resuming the initial configuration after a disturbance.

We can now proceed to enumerating these concepts with formulae. We will approach this in the context of a system with multiple components, such as a network of nodes and connections shown in Figure 1. We can say that this system consists of a minimum number of nodes N_{min} required uninterrupted operation, such as the system shown in Figure 2, and of ΔN additional nodes.
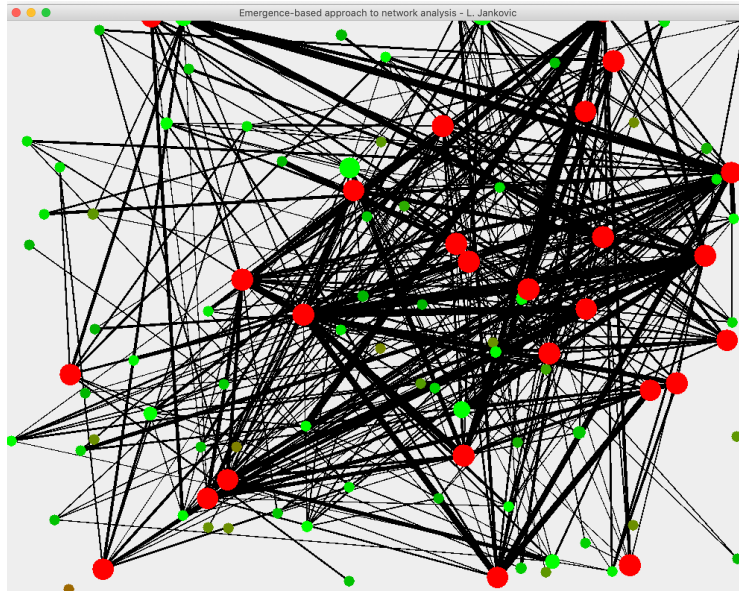
Figure 1 An example of a multi-component system consisting of N_{min} + ΔN connected nodes
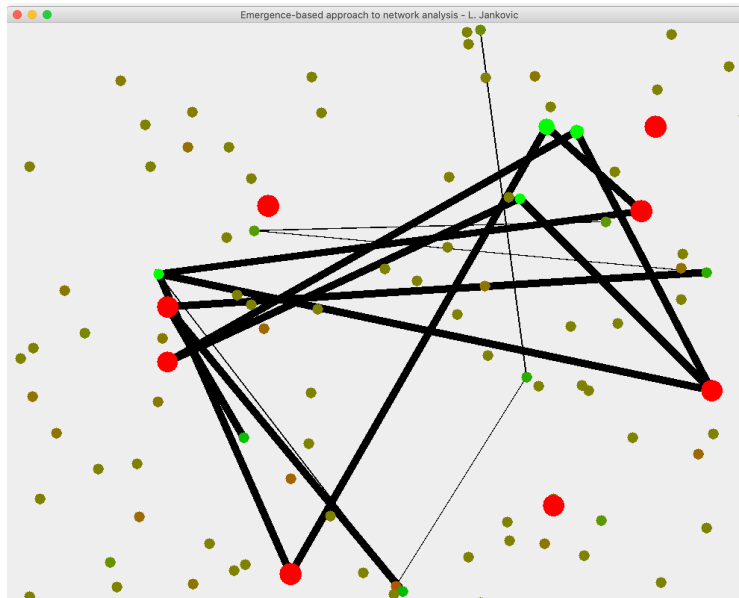

Figure 2 An example of a multi-component system consisting of N_{min} connected nodes

Assuming that the system in Figure 2 will not be capable of operating is a single node is removed, we can say that such system is at the edge of collapse, and that N_{min} enumerates the edge of collapse condition.

We can also say that the difference between the system in Figure 1 and the system in Figure 2 represents the redundancy/spare capacity of the system, enumerated with ΔN. Thus, system robustness can be enumerated as shown in Equation (1):

$$S = \frac{N_{min} + \Delta N}{N_{min}} \tag{1}$$

The system resilience potential can then be enumerated as shown in Equation (2):

$$R = 1 - \frac{N_{min}}{N_{min} + \Delta N} \qquad (2)$$

Discussion

We are now going to test these equations using thought experiments. Let us deal with system resilience first, as expressed in Equation (1). If we expose the system specified with Equation (1) to external disturbance, how much can we remove from that system without a detrimental effect on its operation? The obvious answer appears to be ΔN, the extent of redundancy/spare capacity in the system. By removing ΔN, we will change the system robustness from $S > 1$ to $S = 1$. If, for instance, $N_{min} = 10$ and $\Delta N = 4$, by substituting these values in Equation (1) we can say that the system robustness changes from $S = 1.4$ to $S = 1$ if we remove ΔN.

We now go onto Equation (2). If we expose the system specified with Equation (2) to external disturbance, how much can we remove with the system still standing? Again, the answer is ΔN, the extent of system redundancy/spare capacity. By removing ΔN, we will change the system resilience from $1 > R > 0$ to $R = 0$. Using the same numerical values for $N_{min} = 10$ and $\Delta N = 4$ and substituting them in Equation (2), we can say that system resilience changes from $R = 0.286$ to $R = 0$ when ΔN is removed.

What would this mean in practical terms? For instance, if we say that $N_{min} = 1$ represents the minimum number of hospitals in a region, then the presence of one more hospital can be represented as $\Delta N = 1$. Replacing these values in Equation (1) will result in robustness $S = 2$. A closure of this additional hospital, represented as $\Delta N = 0$, will lead to Equation (1) resulting in robustness $S = 1$.

Applying the above values of N_{min} and $\Delta N = 1$ in Equation (2) will lead to resilience $R = 0.5$. Closing the additional hospital, represented as $\Delta N = 0$, will lead to Equitation (2) resulting in resilience $R = 0$.

Conclusions

The main motivation for this work was to establish a simple measure of resilience that could be applied in multiple contexts, as no such measure that can be easily enumerated exists in the body of resilience research. Starting from Kolmogorov Complexity and the notion of the shortest computer program, the ingredients of system robustness, edge of collapse, redundancy/spare capacity and resilience were established and generalised. This work is in progress and it will be updated through future research.

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