A Generic Quantitative Approach to Resilience: A Proposal

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Abstract. Resilience is the ability to bounce back from a disruption. Of late, applying the concept of resilience to systems and enterprises is gaining importance because major disruptions are becoming more unpredictable, more frequent, and more severe. While there have been some efforts on defining metrics and measuring resilience, there is no generic quantitative approach to resilience that can be used to measure, predict or compare resilience. This paper proposes a generic quantitative approach to defining and measuring resilience. A simple resilience model is introduced using five critical states of a system, and a set of assertions based on a resource based view. These assertions are treated mathematically in the generic resilience model, and a formula for computing resilience is defined. Two simple cases are also discussed to illustrate the usefulness and potential of this approach.

Introduction

Resilience is the ability to bounce back from a disruption. As a technical term, it was introduced by (Holling 1973) in the field of ecology. This concept has been used and developed traditionally in many disciplines like psychology and material science. Over the past decade, systems engineers and managers are showing increased interest in the concept of resilience. With increased complexity, extensive globalization, and increased interdependency, today's systems and enterprises are becoming more vulnerable to many man-made and natural disasters and calamities. Resilience is therefore, a much desired attribute.

The dispersed growth of resilience has led to different definitions, understanding and applications of the concept (Madni and S. Jackson 2009). Carpenter et al. (2001) consider resilience as the magnitude of disturbance that can be tolerated by a socio-ecological system. This concept follows the definition of ecological resilience proposed by Holling (1996). Jackson (2007) considers resilience as the ability to mitigate, adapt and respond. Fiksel (2003) emphasizes that in resilience, structure and function should be retained while tolerating disturbance. Hoffman (2007) states that resilience is the ability to sustain, recover, resume, and continue to provide minimum services. Vogus and Sutcliffe (2007) state that organizations should emerge strengthened and more resourceful after a disruption. Wreathall (2006) adds the element of quickness to resilience. Together, these and other existing definitions fail to provide a clear consistent understanding of the concept of resilience.

Attoh-Okine, Cooper, and Mensah (2009) introduce a resilience index for urban infrastructure using a belief function framework. Bhamidipaty, Lotlikar, and Banavar (2007) present a Resiliency Maturity Index (RMI) for evaluating the resilience of an IT services organization, by quantifying the effect of failures on the organization. RMI uses a Resiliency Maturity Assessment Framework (RMAF) which evaluates six layers of an organization to understand enterprise resilience. Najjar and Gaudiot (1990) propose network resilience (NR) and relative network resilience (RNR) as probabilistic measures of network fault tolerance. Rosenkrantz et al. (2009) define node resilience and edge resilience as two metrics to measure the resilience of a service-oriented network, based on a graph-theoretic model. Reed, Kapur, and Christie (2009) calculate resilience as the area under the quality curve for a networked infrastructure.

Since there are differences in the many definitions of resilience, these quantitative approaches also are not universally applicable. This paper proposes a resilience model that is based on the fundamental nature of resilience, and is not associated with any discipline or application. A generic quantitative approach is presented.

Generic Resilience Model

Five states of resilience

A system passes through five states while exhibiting resilience, as illustrated in Figure 1. The system exists in a stable original state to start with. A disruptive event, which could be a combination of internal and external factors then occurs, that affects the system. As a result, the system goes into a disrupted state. Resilience action is then taken in response, which enables the system to bounce back to a recovered state. Hence, from the resilience perspective, a system passes through five states in the process viz. stable original state, disruptive event, impact/disrupted state, resilience response and stable recovered state.

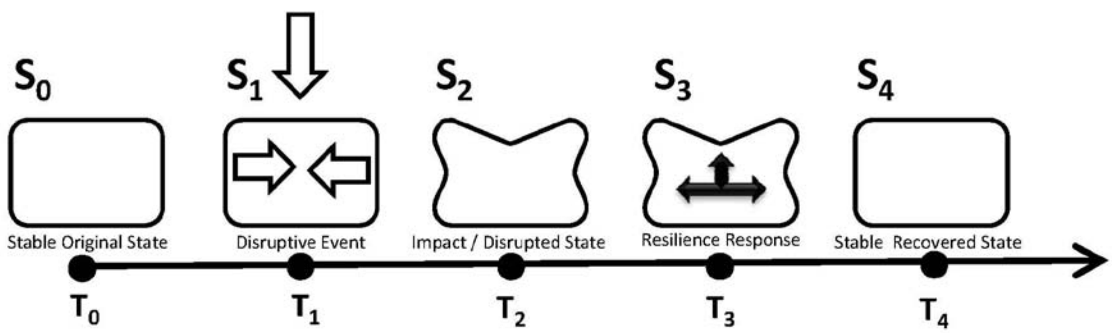


Figure 1: Five States of Resilience

This is a simple model constructed for better understanding of resilience, and to enable a quantitative approach, which is discussed and presented in subsequent sections. It is assumed here that these five states occur discretely and sequentially. In reality, these states could each be a function of time, and could overlap with one another.

Model assertions

The resilience model also makes a few assertions on the nature and characteristics of resilience that help support and enable the quantitative approach presented in this paper.

- The system of interest, during its original stable state, performs a number of functions. These functions are the reason and purpose for its existence.
- The system requires a number of resources in order to perform these functions. The term

'resource' is used here in a broad context, and is not restricted to material or physical resources only. Depending on the system and its functions, the resources could be tangible and/or intangible, including facilities, infrastructure, workforce competencies, procedures, processes, data, and machinery.

- The disruptive event directly affects the effectiveness of the resources that are required by the system, or access to those resources. As a special case, when a resource gets destroyed, its effectiveness becomes zero, and when the source of a resource gets destroyed the system loses access to that resource.
- As a result of the resources getting affected, the system is unable to perform its functions, and so it enters a disrupted state.
- The resilience response to this situation involves restoring the effectiveness of the affected resources, or restoring access, or restructuring the system so that it now needs different types/quantities of resources, or even redefining the functions that the system was unable to perform.
- As a result of the resilience response, the system 'bounces back' and reaches a stable recovered state that could be the same as its original state, or a different but stable one. It is to be noted that during all the in-between states (following the stable original state), the system was in a transition, including during the resilience response. This assertion also indicates that resilience response is not over unless the system reaches a stable state.

It can be seen that the assertions discussed above present the concept of resilience in a way that aligns with the fundamental concept of resilience, which is to 'bounce back'. These assertions provide the basis for a quantitative approach to resilience.

Quantitative Approach

The quantitative approach presented in this section is based on the generic five-state resilience model and the assertions presented above.

System of Interest

The system, whose resilience is of interest, is denoted by **S**. This **S** could be the whole system or a sub-system or a component of an overarching system or even a System of Systems. It is important that **S** is clearly defined and identified as a first step. This helps to draw the system boundary and to identify what is within the system and what is outside. Defining **S** answers the question "Resilience OF what?"

The functions performed by system **S** are captured as performance variables $\mathbf{PV_i}$. These are figures-of-merit (FOM) that should be quantifiable and measureable. While the system could perform a large number of functions, only the functions that are relevant to resilience are identified here. This is an important step, as this provides an explicit answer to the question "Resilience IN what?"

As asserted, the system would require resources to perform its functions, and they are captured as resource variables $\mathbf{RV_i}$. Typically, one or more resources would be required to perform a function. Also, one resource could be required by more than one function. Hence a many-to-many relationship could exist between performance variables and resource variables.

Simple Case

A simple case is used here to discuss the quantitative approach. Only one function of a system is considered here. Therefore, only one performance variable **PV** of a system **S** is considered. Further, it is assumed that this function requires only one resource. Hence, the performance variable **PV** is a function of a single resource variable **RV**. There are many attributes of the resource variable that are implicitly considered – e.g. quantity, efficiency or effectiveness, and accessibility. However these attributes are not explicitly considered in the quantitative approach for now.

The state of the system **S**, the value of the performance variable **PV** and the value of the resource variable **RV** at an instant of time **T** are denoted by $\mathbf{S_T}$, $\mathbf{PV_T}$ and $\mathbf{RV_T}$ respectively. The state of the system $\mathbf{S_T}$ is a function of the single performance variable and the performance variable $\mathbf{PV_T}$ is a function of the resource variable $\mathbf{RV_T}$ as shown in (1) and (2).

$$\mathbf{S_T=f(PV_T)} \quad \mathbf{(1)}$$

$$\mathbf{PV_T=f(RV_T)} \quad \mathbf{(2)}$$

Five states of resilience

The resilience of the system **S** is discussed during each of the five states of resilience identified in the generic resilience model, illustrated in Fig. 1. At each state, the status of $\mathbf{S_T}$, $\mathbf{PV_T}$ and $\mathbf{RV_T}$, and the relationships between them across different states bring out the proposed quantitative approach.

State 0: Stable Original State

At the start of the study, $\mathbf{T_0}$, the system exists in a stable state $\mathbf{S_0}$, performing its single function $\mathbf{PV_0}$ requiring a single resource $\mathbf{RV_0}$. This state serves as the reference baseline that helps compare the states of the system when it gets disrupted and later on when it recovers.

State 1: Disruptive Event

The disruptive event, which could be a combination of external and internal events, occurs at time $\mathbf{T_1}$. It is assumed here that at this instant of time, only the resource $\mathbf{RV_1}$ gets affected and not the system level performance variable. As discussed, either the quantity or efficiency of a resource or access to it may get affected. In any case, $\mathbf{RV_1}$ would be less than $\mathbf{RV_0}$ as shown in (3).

$$\mathbf{RV_1<RV_0} \quad \mathbf{(3)}$$

State 2: Impact / Disrupted State

As a result of the disruptive event and the drop in the resource variable, the system is unable to exhibit its original level of performance. No further deterioration of the resource variable is assumed, and therefore the values of $\mathbf{RV_2}$ and $\mathbf{RV_1}$ are equal, as shown in (4). However the performance variable $\mathbf{PV_2}$ and the system state $\mathbf{S_2}$ get affected here at $\mathbf{T_2}$. Therefore, performance variable $\mathbf{PV_2}$ is less than its original value $\mathbf{PV_0}$ and the state of the system $\mathbf{S_2}$ is worse than the original state $\mathbf{S_0}$ as shown in (5) and (6).

$$\mathbf{RV_2=RV_1} \quad \mathbf{(4)}$$

$$\mathbf{PV_2 < PV_0} \quad \mathbf{(5)}$$

$$\mathbf{S_2 \prec S_0} \quad \mathbf{(6)}$$

It must be noted here that in order to exhibit resilience, the system must go into a disrupted state. If the disruptive event does not deteriorate the performance of the system, then the system cannot display resilience. Such a situation where the system does not enter a disrupted state even after a potentially disruptive event, exhibits other attributes of the system, like robustness or reliability. Hence the presence of a disrupted state distinguishes resilience from other similar concepts.

State 3: Resilience Response

The system exhibits resilience when it bounces back from its disrupted state. Based on the generic model and assertions presented earlier, it can be seen that this is achieved by influencing the resource variable. Resilience action is taken here at time $\mathbf{T_3}$, by adding $\boldsymbol{\delta}\mathbf{R}$ to the resource variable $\mathbf{RV_2}$, as shown in (7). Now this resilience action could influence the quantity, efficiency, or accessibility of the resource, whichever has been affected by the disruptive event. As a result, the resource variable is now higher than earlier, as shown in (8).

$$\mathbf{RV_3 = RV_2 + \delta R} \quad \mathbf{(7)}$$

$$\mathbf{RV_3 > RV_2} \quad \mathbf{(8)}$$

Since the performance variable is a function of the resource variable, an improvement in the value of the resource variable $\mathbf{RV_3}$ will improve the value of the performance variable $\mathbf{PV_3}$, as shown in (9). And this results in improving the state of the system $\mathbf{S_3}$, which is now better than the state of the system during the disrupted state $\mathbf{S_2}$, as shown in (10). While the resilience action improves the system state from its disrupted state, this is still a transient state.

$$\mathbf{PV_3 > PV_2} \quad \mathbf{(9)}$$

$$\mathbf{S_3 \succ S_2} \quad \mathbf{(10)}$$

State 4: Stable Recovered State

The objective of the resilience action is to bring the system to a stable recovered state $\mathbf{S_4}$. In order to study resilience, it is required to compare the stable recovered state at time $\mathbf{T_4}$ with the stable original state at $\mathbf{T_0}$. This stable recovered state $\mathbf{S_4}$ could be worse than, equivalent to, or better than the stable original state $\mathbf{S_0}$, as shown in (11). These relationships are valid for the performance variable as well, as shown in (12)

$$\mathbf{S_4 \prec S_0 \text{ or } S_4 \equiv S_0 \text{ or } S_4 \succ S_0} \quad \mathbf{(11)}$$

$$\mathbf{P_4 < P_0 \text{ or } P_4 = P_0 \text{ or } P_4 > P_0} \quad \mathbf{(12)}$$

Further, the stable recovered state $\mathbf{S_4}$ must be better than the disrupted state $\mathbf{S_2}$, as shown in (13) and (14). If not, this will indicate that the resilience action taken during $\mathbf{T_3}$ has been ineffective or inefficient, and that the improvement seen during that state, as shown in (10) was only temporary, and that there is no recovery with respect to the loss that the system suffered.

$$\mathbf{S_4 \succ S_2} \quad \mathbf{(13)}$$

$$P_4 > P_2 \qquad (14)$$

Resilience Formula

Resilience of a system is defined as the ability to bounce back from a disruption. This implies that the system went into a disrupted state as a result of the disruptive event, and then recovered or bounced back from it. Using the generic five-state resilience model presented earlier, a system that was in a stable original state $\mathbf{S_0}$, deteriorated to a disrupted state $\mathbf{S_2}$ and then bounced back to a stable recovered state $\mathbf{S_4}$.

Resilience **Я** of a system can therefore be defined as the ratio of the **recovery** to the **loss**, expressed as a percentage, where **loss** is the amount of deterioration from the original state to the disrupted state and **recovery** the amount it bounces back from the disrupted state to the recovered state, as shown in (15). This formula computes resilience as a percentage.

$$\text{Я} = (\text{Recovery}/\text{Loss}) \times 100 \qquad (15)$$

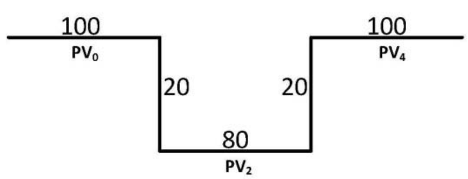
In the quantitative approach to resilience presented earlier, we have introduced the performance variable **PV** as the quantitative figure of merit which denotes the variable that is of interest to resilience. Hence, for the simple case discussed earlier, resilience can be defined as shown in (16).

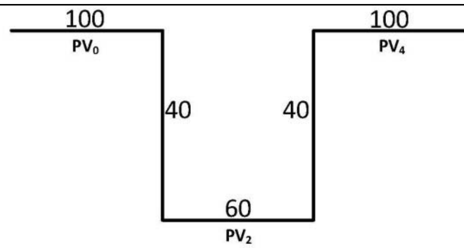
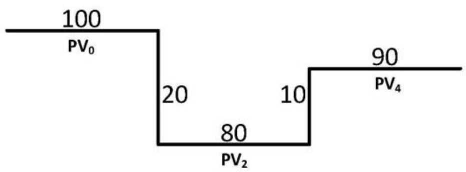
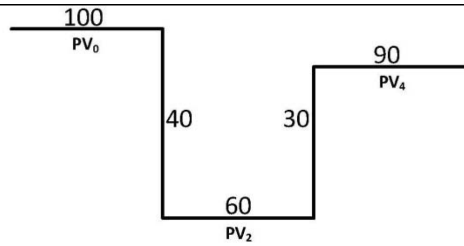
$$\text{Я} = ((PV_4 - PV_2)/(PV_0 - PV_2)) \times 100 \qquad (16)$$

Sample Calculations

A few sample calculations are presented here to explain the usage and for better appreciation of the proposed resilience formula. Consider a system **S** with a **PV** value of 100 during its stable original state. Four sample cases for that system are shown in Table 1, where the value of **PV** at $\mathbf{T_0}$, $\mathbf{T_2}$ and $\mathbf{T_4}$ i.e. the original state, disrupted state and recovered state, are given. The resilience **Я** for each case is calculated using the formula shown in (14).

Table 1: Sample Calculations

#	Case	PV_0	PV_2	PV_4	Я
1		100	80	100	100%

2		100	60	100	100%
3		100	80	90	50%
4		100	60	90	75%

In cases 1 and 2, the system recovers back to its original **PV** value of 100 and hence the resilience is 100%, indicating that the system bounced back fully from its disruption. Even though the disrupted state in case 2 was more severe than the disrupted state in case 1, the system was able to recover back to its original state. Hence, in both these cases (1 and 2) the system is considered to exhibit 100% resilience.

In cases 3 and 4, the system could only recover ½ and ¾ of the disruption respectively, and this is indicated by their resilience values of 50% and 75% respectively. Here again, though the actual values of the loss and recovery are different in cases 3 and 4, resilience is computed based on the recovery compared to the loss.

Usefulness of the Proposed Generic Quantitative Approach

The proposed generic resilience model and formula are discussed here, using two simple case studies. These cases show that the model is able to capture real-life cases of resilience. Further, the model also enables development of resilience strategies for future disruptive events.

Case 1: IT System/Enterprise

Cantor Fitzgerald is a financial trading house that plays an important role in the U.S. Government Treasuries market, brokering trades worth $1 trillion every week, as per 2001 data (Sheffi 2005). Cantor's offices were located on the 105th floor (and a few floors below) of the North Tower of the WTC in New York. On September 11, 2001, a hijacked plane hit the North Tower a few floors below Cantor's offices, and then the tower collapsed a couple of hours later. All of its employees who were at work when this event happened died, and all machines were destroyed along with all the data and software they held. But less than 2 months after this disaster, Cantor was back to handling 100% of its usual volume of bond trading and 80% of its usual level of stock trading.

Eventually, it fully recovered to its original level of trading before September 11, 2001.

Based on the generic resilience model described in this paper, we can see that IT systems (hardware and software) and skilled personnel (traders, analysts and other employees) were the two main resources that helped Cantor perform its various trading functions. The levels of bond trading and stock trading are the figures of merit or the performance variables. As a result of the disruptive event (collapse of the North Tower), these resources were affected, and hence Cantor was unable to handle its usual levels of trading. This loss in the levels of bond trading and stock trading was recovered by restoring the IT systems and recruiting the people with the required skills. Eventually, Cantor fully recovered from its loss and hence displayed 100% resilience.

The resilience action was enabled by two important factors:

1. The entire IT system, and all its functionalities, was replicated at a site in New Jersey, and a third site in London, UK. This enabled the data and the software to be recovered.
2. Fortunately, the CEO of Cantor was late for work on September 11, 2001 and hence he survived the disaster that destroyed the rest of his New York WTC office.

The first factor brings out the importance of redundancy as a resilience strategy. In IT, it is common to have disaster recovery strategies as part of business continuity planning, since IT is the backbone for almost every business and enterprise today. This strategy enables data and functionality of the IT systems to be available even when disaster strikes – whenever, wherever, however. Similarly, people with specific skills and competencies are also required. While manpower may be available, the desired skills in the workforce may need to be developed – a good resilience strategy should consider these issues. This focus on the resources that are required to perform the functions of the enterprise helps form an effective resilience strategy.

The second factor brings out the fact that resilience is a willful action that makes decisions to be taken. In this case, it was the surviving CEO who initiated and performed the resilience action.

Case 2: Infrastructure System

It is typical for infrastructure systems like roads, communication networks, water supply, and power supply to get affected by various manmade or natural disasters. Earthquakes for example, depending on their intensity and geographical location, can destroy infrastructure even if it was designed to be earthquake-resistant. It requires clearing of the damage and reconstruction to restore the infrastructure that was destroyed. Cities that are able to re-build their infrastructure are said to be resilient. The loss of life and personal property and their impact on individuals, families and communities is not discussed here.

Based on the generic resilience model described in this paper, it can be seen that the roadways infrastructure system utilizes the (physical) roads as the resources to achieve the function of proving a means for road vehicles to travel on. To enable a quantitative approach, a figure of merit called “availability” could be defined as shown in (17).

$$\mathbf{PV = (Length\ of\ usable\ roads\ /\ Total\ length\ of\ roads) \times 100} \qquad \mathbf{(17)}$$

The roads (or resources) get destroyed as a result of the disruptive event – earthquake. This loss will be captured as a drop in "availability", since portions of the roads will become unusable. Resilience action involves repairing these unusable sections of roads and making them usable again. As a result, the roadways system will recover. When all the roads are ready to be driven upon, then "availability" becomes 100% (or its original value) and it can then be said that the road infrastructure system is 100% resilient.

Resilience Strategy

As can be seen from the two cases discussed earlier, the generic resilience model and the quantitative approach capture the complete resilience event – from the original state, disruptive event, the impacted state, resilience action and finally the recovered state. It can also be seen that the ability to restore resources that are affected due to a disruptive event is key to resilience. This is an important contribution of this resilience approach. It is valuable to evaluate the resilience of a system based on its response to a disaster that happened in the past, or to compare the resilience of two systems that were affected by the same disruption. However, it is more valuable to be able to design and resilience strategy that would enable a system to recover from a disruption that is yet to happen. The proposed quantitative approach to resilience enables such resilience strategies to be designed and implemented. However, this approach is still in its early stages and needs to be developed further.

Further Research and Concluding Remarks

The quantitative approach to resilience presented here makes a number of simplifying assumptions. While this is required to define the basic approach and to plan a research strategy, these assumptions need to be progressively relaxed. The model needs to be refined, improved, and tested in order for the 5-state resilience model and formula to become a useful resilience tool.

The 5-state model currently considers the 5 states to be discrete events in time. The model does not capture how each of these states behaves as a function of time, and also does not consider overlaps of the various states - both of which can typically be observed in real life situations. Adding realism to the model enables detailed analyses and simulations to be performed, but that would also require complex models driven by realistic data.

The resilience formula currently only considers the loss and recovery of the system with respect to the figures-of-merit or performance variables. The resilience action is not directly captured here – it is assumed that a good recovery strategy would recover a disrupted system back to its original level of performance. Two important attributes of the resilience action that are presently not considered, are time and cost. Based on the approach presented here the objective of the resilience action is to recover the disrupted system to a stable state. This action would take time and money. The cost of restoring lost resources or repairing damaged resources also need to be considered. A good resilience strategy therefore, is one that restores a system back to its original level of functionality in minimum time with minimum cost.

When the proposed resilience formula is used to predict resilience in future, it would become stochastic in nature and would lead to considering resilience as a design driver. It would also help develop effective resilience strategies.

While further research is required to bring in the above improvements, this simple approach presented here is found to be useful in understanding the concept of resilience in the context of systems and enterprises. With a focus on resources, the functions they enable to be performed, and the relationship between these two and the resilience of a system, this quantitative approach gives a different pragmatic perspective to resilience. Most importantly, the proposed generic quantitative approach and resilience model enable new systems and enterprises to be built for resilience or for resilience to be injected into existing systems.

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BIOGRAPHY

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