Chapter 11
Infrastructure Resilience

The pioneers will be those countries able to benefit from the opportunities presented by the new economy which, at the same time, will be ready to master the challenges, changes and problems generated by attempts to adapt to it – creative and agile countries that thrive on knowledge, information and ideas.

Mohammed bin Rashid Al Maktoum

Infrastructure design is defining an infrastructure system that will meet the customer’s goals for Functionality, Availability, Manageability, Performance, Efficiency, Recoverability, and Security.

Craig Risinger

Not only must Justice be done; it must also be seen to be done. (The King v Sussex Justices, Ex parte McCarthy ([1924] 1 KB 256, [1923] All ER Rep 233))

Similarly, infrastructure must not only be implemented, but must be seen to perform excellently.

Taken together, this intellectual edifice is an extraordinary testament to human ingenuity. But the whole is no stronger than its weakest member.

B. B Mandelbrot., R. L Hudson

It has been said, by engineers themselves, that given enough money, they can accomplish virtually anything: send men to the moon, dig a tunnel under the English Channel. There’s no reason they couldn’t likewise devise ways to protect infrastructure from the worst hurricanes, earthquakes and other calamities, natural and manmade.

Henry Petroski

Les vents me sont moins qu’à vous redoutables
Je plie, et ne romps pas.
The winds for me are much less dangerous than for thee; I bend, but do not break.

Jean de la Fontaine (Le Chêne et le Roseau)
The concept of vulnerability implies a measure of risk associated with the physical, social and economic aspects and implications resulting from the system’s ability to cope with the resulting event. Resilience implies the ability of an infrastructure system to perform properly even when placed under pressure or the ability of the infrastructure systems to absorb and recover from the impact of disruptive events without fundamental changes in function or structure. Based on what is required to face disasters, features should be inbuilt in the infrastructure (design, normal operation, etc) so as to offer better, if not complete, resilience to the system. As resilience increases, the degree of damage for a given intensity hazard decreases. Measuring resilience is not easy as this depends on the infrastructure system under study. It is important to look at the ways resilience is being considered and use these as a method to measure resilience, either qualitatively and quantitatively. Several approaches have been proposed in this chapter to measure or compare resilience of two infrastructure systems.

11.1 Vulnerability and Resilience

11.1.1 Vulnerability

A water supply network must ensure that the consumer obtains water when she needs it. By extension, Fig. 11.1 shows what a customer expects from an infrastructure system or service.

The concept of vulnerability implies some risk combined with the level of social and economic liability, and the ability to cope with the resulting event. Vulnerability has been defined as the degree to which a system, or part of a system, may react adversely during the occurrence of a hazardous event.

Thus people become “vulnerable” if access to resources either at a household, or at an individual level is the most critical factor in achieving a secure livelihood or recovering effectively from a disaster. The households with direct access to capital, tools and equipment, and able-bodied members are the ones which can recover most quickly when a disaster strikes. As such, the most vulnerable people are the poorest, who have little choice but to locate themselves in unsafe settings.

11.1.2 Resilience of Systems

When a car is moving on an uneven road surface, the car will transmit, to the passengers, the respective shocks sustained whenever the car goes over a hump or into a pothole. But, if the shock absorber (car damping system) is excellent (or should we say efficient), the shocks might only be slightly noticeable. Sometimes, these passages over humps or potholes are even enjoyed by children as they slowly return to a more stable position. This is possible because the car springs are
able to absorb and recover from the shock impacts resulting from the uneven road surface.

In contrast, however, even when a boxer hits his practice sand bag repeatedly, it behaves differently. It barely moves. It is as if he were just hitting a brick wall which does not move at all.

In all the examples above, the system (car, sand bag, brick wall) has some properties or characteristics which allows it to return (or to recover) to the original position or state. This is the concept describing the resilience of a system – the ability of a system to return to its previous stable position (quickly or slowly) after a disturbance or shock. Figure 11.2 illustrates how a system recovers to its normal performance.

In essence, the concept of resilience (Moench 2009) may vary between two extremes:

(a) **hard resilience**: (the brick wall) – the structures or institutions are designed to be strong, so strong that when placed under pressure, there is little probability of collapse. If required, the resilience of a structure may be increased through specific strengthening measures to reduce further this probability of collapse.

(b) **soft resilience**: (the reed of the parable) – systems are able to absorb and/or recover from the impact or shock of disruptive events. There are no fundamental
changes in function or structure, depending on the flexibility and adaptive capacity of the system as a whole. There is no specific strengthening measure contrary to the hard resilience form.

Figures 11.3 and 11.4 describe the difference in behavior between hard and soft resilient systems.
11.1.3 Sectors Needing Resilience

Disturbances or shocks, such as floods, hurricanes, earthquakes, economic crisis, whenever they occur, do affect the performance of existing infrastructure goods or services (to name, just a few, roads, drains, buildings, hospitals, industry). The performance of these sectors gives a good idea of the resilience of such systems or sectors.

Table 11.1 provides a list of infrastructure systems which affect everyday life, and which may be critical in enabling a normal day’s work. Therefore, it is not difficult, once it is understood, to extend the concept of resilience to the range of sectors, as shown in Fig. 11.5.

Fig. 11.4  Soft resilient systems

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Figure 11.2 shows quick and slow possible responses to disturbances. Generally, the system behaves in one of these ways, because most likely, it has been designed, on purpose, to do so, and not just by chance. Broadly speaking, (Handmer and
Dovers (2009) three possible responses suggest themselves whenever a possible disturbance is likely to occur:

1. Resistance and maintenance

The classical “resistance to change” is characterised by the human system which tries its best to avoid change and which may even deny that a problem exists.

2. Change at the margins

Acknowledge the problem, discuss the possible implications, and, probably, accepting that the existing system is not sustainable, and therefore requires change.

3. Openness and adaptability

Besides acknowledging the problem, being highly flexible reduces vulnerability. There is a preparedness and willingness to assume and adopt new basic operational and institutional structures.

These possible responses are varied partly because (1) the cost of resilience provision is usually borne by taxpayers, private individuals, and private enterprise and (2) the latter are not, normally, those who decide on the cost/benefit analysis in a competitive and changing, environment. The infrastructure services identified in Table 11.1 can hardly be thought of being independent of each other. Thus, if any one were affected (disrupted, disturbed) during a disaster, it would most probably affect another one (if not a few others). Therefore, given that lack of resilience can destroy structures, harm workers, affect the population, the costs of resilience and expected benefits can only be assessed using a holistic viewpoint before deciding on sound investment strategies.

Infrastructure resilience, thus, now becomes, an integrated goal of identifying the time, cost and other resources required to restore the existing overall infrastructure to its full functionality, as prior to the disruption or disaster.

11.1.4 Definition of Resilience

After the above discussion, system resilience may now be defined is as follows:

A system is usually designed to behave in a certain way under normal circumstances. When disturbed from equilibrium by a disruptive event, the performance of the system will deviate from its design level. The resilience of the system is its ability to reduce both the magnitude and duration of the deviation as efficiently as possible to its usual targeted system performance levels.

System resilience will be influenced either by inherent properties or those built in the system. More particularly, improved resilience may be obtained by defining, quantifying, and designing through three such properties or capacities:
Table 11.2 Resilience capacities of a system (after Proag 2014a, b)

| Component                  | System impact                              | Total recovery effort                                           |
|----------------------------|--------------------------------------------|-----------------------------------------------------------------|
| System capacities          | Absorptive. Endogenous feature             | Adaptive dynamic ability to change endogenously                 |
|                            | Capacity’s normal features Acts immediately after shock absorbing the impacts of system disturbance with little effort | Actions taken over time after the shock, to move towards recovery |
| Examples                   | Storage can act as a buffer for flood water | Standby generators in case to cater for power breakdowns         |
| Effort required            | Automatic/little effort                    | Internal effort required                                        |
| Enhancement features       | System robustness – bigger drain, stronger beam | Possibility of substituting components                          |
|                            | System redundancy – alternate pathways, parallel circuits | Often rely upon the ingenuity of people faced with adversity |
|                            |                                            | Food substitutes                                                 |
| Measurement of component   | Internal measurement                       | Internal measurement                                            |
|                            | Important in the initial stages of disruptions | Important in the initial stages of disruptions                   |
|                            |                                            | Exogenous measurement                                           |
|                            |                                            | Repair of the system might be impossible in the short term      |

(1) absorptive capacity – or can the system, partly or completely, absorb the disruptive event;
(2) adaptive capacity, or can the system, partly or completely, adapt to the disruption;
(3) restorative capacity, or can the system, partly or completely, recover after the event

Table 11.2 gives a summary of the characteristics distinguishing the capacities.

11.1.5 Relationships Between System Capacities, Performance, and Recovery

Table 11.3 illustrates how a system depending on another, or other supports across systems can influence (usually reduce) resilience capacities.
11.1.6 Resilience Enhancement Features and Resilience

Features which enhance resilience are often closely connected to the specific sector being considered (See Table 11.4). When examining the long-term behaviour and sustainability of companies, ecosystems, and social systems, Fiksel (2003) determines four types of characteristics of resilient systems which are resilient enhancement features, as well, namely:

(1) diversity, or “existence of multiple forms and behaviours”;
(2) efficiency, or “performance with modest resource consumption”;
(3) adaptability, or the “flexibility to change in response to new pressures”; and
(4) cohesion, or the “existence of unifying forces or linkages.”

Table 11.3 Relationships between system capacities, performance, and recovery

| Capacity | Relationships |
|----------|---------------|
| Absorptive | System A (buses, lorries) depends upon system B (roads) for operation. If system B is negatively affected (damaged or closed roads, accidents) this dependency reduces system A’s absorptive capacity in such scenarios. |
| Adaptive | A heater/boiler (system A) may be designed to use different fuels (wood, gas, oil or other fuel). With this adaptive capacity, system A does not wholly depend on system B (oil) and has thus reduced its dependency on system B (oil). |
| Restorative | A gravity pipeline (system A) works independently of electrical power or road access (system B). However, repairs on system A may require that system B be operational. During or after disasters, difficult institutional coordination may further decrease restorative capacity. |

Table 11.4 Enhancement features in different sectors

| Sector | Enhancement features |
|--------|----------------------|
| Technical | These are features or technical solutions that try to increase the performance level of the infrastructure service. A simple design is often robust, easy to adapt and easy to repair. These properties translate into being more absorptive, more adaptable and more restorable. |
| Organisational | Considering the absorptive, adaptive, and restorative properties of the system, the institutions and organizations should select an optimal recovery approach by comparing the recovery period against the costs involved. |
| Economic | After a disaster, a scarce resource – at high prices – finds a reduced demand. If such price increases are prohibited, a non-resilient (or even negatively resilient) system may result because the absorptive and adaptive capacities of resilience generated by the market price system are reduced. |
| Social | Very often, after a disaster, neighbours will team up their resources and start reconstruction – without waiting for government aid with the traditional delays – or, just to help another neighbour. Here, the community local characteristics often enhance the social resilience capacity. |
11.2 Assessing Infrastructure Resilience

Table 11.5 explains the steps that can be carried out for assessing the resilience of social-economic systems. (Resilience Alliance 2007a, b).

The absorptive, adaptation and restorative properties of a system determine its resilience. Just as efficiency is the ratio of output to input, one can imagine defining a resilience efficiency as

\[
\text{Resilience efficiency} = \frac{\text{Output under (or after) Shock}}{\text{Normal Output}}
\]

Variations based on this will be discussed further down when dealing with quantitative assessment.

While output is usually a measure of performance, the time taken to return to normal performance can also be another measure of resilience, as well as the effort (cost, resources) required to do so.

A simple example: a damaged house does not have the same amenities as prior to the disaster. How much time and effort (cost) are required to get the house performing as before?

Table 11.6 gives some performance examples which may be utilised as a measure (metric) for certain infrastructure and economic systems. The list is, of course, non-exhaustive.

| Steps                        | Explanation                                                                 |
|------------------------------|-----------------------------------------------------------------------------|
| Explore the system           | To identify the different system components and how the system becomes resilient. |
| Identify the critical resilient components | To identify the system boundaries, determine appropriate scales to assess resilience, and identify the relevant variables of interest. |
| Identify where sector resilience is required | From stakeholders and a historical log, to list down possible external disruptive events or shocks and corresponding internal parameters. |
| Identification of stakeholders | To determine the main players and the relevant external critical parameters. |
| Assessment of resilience     | To determine, through models, possible recovery paths and the corresponding recovery efforts required. |
| Management implications      | To inform decision or policy makers or managers how the system components might or not be vulnerable to shocks. |
| General assessment of resilience | To prepare a general synthesis of the findings above, with recommendations. |
11.3 Qualitative Assessment

11.3.1 Risk Analysis Approach

Usually, when implementing a project, a risk analysis is carried out prior to and during project execution, as shown in Table 11.7. A complete brainstorming is effected in order to identify the maximum number of possible risks to the project.

Once the risks have been compiled, the project team assesses, for each risk:

1. the occurrence probability on a scale of 1–9 and
2. the impact on the project if the risk does occur.

Thus, all risks are rated as per Table 11.8.

The details explaining the above impact classification of Table 11.8 are provided in Table 11.9. These are useful in determining the dangerous zones to avoid.

11.3.2 Resilience Assessment Approach

Thus, using a similar approach, the system under scrutiny, may be assessed for its resilience qualitatively, as detailed in Table 11.10.

Issues identified are ranked based on their impact and expected consequences by assigning a red, yellow or green flag. These determine the duties of those responsible, as shown in Table 11.11.

| Table 11.6 Possible performance metrics |  |
|----------------------------------------|--|
| Infrastructure system | System performance metrics |
| Agriculture and food | Average food price, exposure to food contamination, local production, imports |
| Chemical | Air pollution, water contamination |
| Communications | Number of dropped telephone calls |
| Emergency services | Number of lives saved; average response time |
| Energy | Consumption, profitability of energy companies, outage hours |
| Information technology | Number of cyber attacks, internet access speed |
| Public health and healthcare | Mortality rates, patient attendance |
| Transportation systems, highway | Average speed and cost of shipments; length of traffic jams |
### Table 11.7 Risk analysis

| Risk approach | Activity carried out |
|---------------|----------------------|
| Identification| Determine the type and possible source of risks. |
| Classification| Consider the type of risk and its impact on the organisation or person. |
| Analysis      | Assess and determine the consequences related to the type of risk, or combination of risks, through analytical techniques. Evaluate the impact of the risk through various risk measurement approaches. |
| Attitude      | The attitude of the decision taking person or organisation will influence the decision about the risk. Risk averse persons are quite reluctant about taking any risk. |
| Response      | Managing a risk implies that after identification, it should either be retained or be transferred to a third party. |

### Table 11.8 Risk probability and impact parameters

| Probability | Impact on the project |
|-------------|-----------------------|
|             | Low | Medium | High |
| 7–9         | Medium | High | Unacceptable |
| 4–6         | Low | High | Unacceptable |
| 1–3         | Low | Medium | High |

### Table 11.9 Impact classification and related action

| Impact class | Description |
|--------------|-------------|
| High         | The project schedule will be seriously affected, with increased costs, and serious resulting impacts on other associated projects. A project milestone will probably be affected. This risk should be, carefully and regularly, monitored. |
| Medium       | The project will be significantly impacted with a possible impact on other associated projects. No project milestone is likely to be affected. This risk should be reviewed, however, at each project meeting and its ranking assessed. A regular monitoring is necessary. |
| Low          | No serious impact on the project is expected from this risk, which, however, needs to be reviewed regularly for ranking and monitoring. |

### Table 11.10 Qualitative assessment of system resilience under shock

| Resilience assessment step | Activity carried out |
|---------------------------|----------------------|
| Identify system and subsystem(s) | System boundaries enable the resilience assessment to be of manageable size. |
| Identify system performance metric(s): | The stakeholders should be able to understand the metrics selected and their purpose. |
| Assess or simulate the possible recovery path | Identify, after the disaster, the impacts to the system and possible changes during the recovery period. |
| Assess or simulate the required recovery effort | The recovery path is influenced by the recovery effort. Both will likely use similar qualitative or quantitative approaches. |
| Identify the resilience enhancement features and assess the resilience properties | Identify system features that affect resilience properties. |
11.4 Quantitative Assessment

11.4.1 Resilience Efficiency

As explained earlier, while output is usually a measure of performance, the time taken to return to normal performance can also be another measure of resilience, as well as the effort (cost, resources) required to do so.

If we define the concept of Resilience efficiency as:

\[ \text{Resilience efficiency} = \frac{\text{Output under (or after) Shock}}{\text{Normal Output}} \]

it is logical to use the same principles to introduce the recovery time and the effort required in a quantitative estimate of resilience.

11.4.2 Resilience Quality

If two similar systems are equally damaged, the time it takes for them to recover back to normal performance can be a simple measure for resilience (cf. Figure 11.2). The longer time it takes, the less resilient it is.

With hard resilience, the system resists completely to the shock. Practically, the system performs as previous to the impact. Figure 11.3(a) shows this. A building subjected to a wind gust behaves like this. During a lightning flash, the electricity supply may momentarily be cut during a fraction of a second. However, during a hurricane, the power supply may, on purpose, be interrupted for security reasons, such to avoid anybody touching broken (overhead) cables, etc. This time, the interruption is longer, but after the event, performance is back to normal. (See Fig. 11.3(b)).

However, as Fig. 11.4(a, b, c and d) shows, the system may be only partly functional, say at \( y \% \), \( y \) varying with time, during this recovery period. The variation of \( y \) with time may be linear, logarithmic, exponential or even erratic (Fig. 11.6).

If this percentage \( y \% \), is plotted on the y-axis (Figs. 11.3 and 11.4) against time, the area under the curve gives a better metric of the product (performance x time). Had there been no damage, the area under the curve would have been 100% x recovery period, still showing a 100% functionality. Thus, the ratio of the area \( A \) to

| Table 11.11 | Responsibility allocation for possible issues |
|-------------|---------------------------------------------|
| **Red flag** | Major issue with important consequences for the project. A quick action is required to implement a decision. It may be due to a delayed action from a yellow flag. |
| **Yellow flag** | Significant consequence for the project and associated projects. Delays to milestones may occur unless immediately resolved. If action is delayed for more than 2 days, it turns into a red flag. |
| **Green flag** | The consequences are confined to the project area, and are unlikely to affect other project zones. However, if it is not timely resolved, it turns into a yellow flag. |
the area B in Fig. 11.6 can give a quantitative measure of resilience that could be termed as **resilience quality**.

### 11.4.3 Effort (Cost) Resilience

Another possible metric is to determine the effort (cost) (X) required to return to normal performance. Obviously, if X = 0, it can be said that the system is 100% resilient. At the other extreme, 0% resilience would imply complete destruction, and a new system is required.

Let this effort (cost) needed to construct a new system performing as before, be Y. Comparison of Y against X can then be used to define an effort (cost) resilience. The effort (cost) resilience could then be defined as

\[
\text{Effort (cost) resilience} = \frac{Y - X}{Y}
\]

This ratio gives 0% if the complete system has to be rebuilt, and 100% if no effort (cost) is required.

Figure 11.7 shows the situation on a graph.
If \( X \) is displayed on the x-axis, and \( Y \) on the y-axis, any value of \( Y \) when \( X = 0 \) indicates a 100% resilience. This is shown by the thick line on the y-axis.

If the repair (restorative) cost (effort) is the same to build a new system, then \( Y = X \). This is shown by the thick line of \( Y = X \) on the graph, which represent 0% resilience.

The region between these two thick lines represents actual resilience. The nearer the actual resilience is to the 100% line, the better.

**Fig. 11.7** Resilience quality results
11.4.4 Comparison

It may be observed that this last resilience metric would still give 100%, even if the system – though requiring no effort (cost) – takes a considerable time to recover to normal performance. It is therefore judicious to associate several resilience metrics to assess or compare different systems.

11.5 Using Cost Benefit Analysis for Resilience

11.5.1 General Principles

Governments and public authorities (local, regional, and central governments, and international donor institutions often use the cost-benefit analysis (CBA) approach for assessing the benefits accruing to society from public investment projects and policies. The CBA technique has been generally used to systematically determine the costs and benefits, and inherent possible trade-offs, and to finally evaluate the economic efficiency of projects. (Dasgupta and Pearce 1986). Although there are several levels of complexity and detail, Table 11.12 gives a good description of the principles and general features of CBA.

Certainly, the discussion on resilience above has been the potential benefits accruing to the infrastructure system and to the users. The works required to introduce (further) resilience into the system should certainly work if ever given the chance, but given the notion of probabilities, the main argument from opponents might be what if the 1000 year event (flood) does not occur during our lifetime? Has the resilience component been introduced for nothing?

There are two major types of cost-benefit analysis, but others are explained in Table 11.13.

| Table 11.12 | Main principles and features of CBA |
|-------------|-------------------------------------|
| Principles  | Features                            |
| 1 With and without approach | The system with and without the project/investment are compared, not the system before and after. |
| 2 Focus on “best option” selection | Is it desirable to undertake a project per se, is not the question. CBA is used to select the best option. |
| 3 Societal perspective | As societal welfare is under consideration, societal benefits must outweigh the costs to render the project component desirable. |
| 4 Revealed versus expressed preferences | The revealed preference approach uses observed market prices for the goods under scrutiny (e.g. the value of material used for rebuilding a structure after a disaster). The expressed preference approach uses preferences gathered through surveys. |
| 5 Clear system boundaries for the analysis | Only losses within the system boundaries need to be counted. Impacts or offsets outside the system boundaries should not be counted. |
It is useful to elaborate on the values of these four types of CBAs.

The ex ante analysis helps to decide whether it is worth allocating resources to a particular project that is being considered. Before it starts or goes to implementation, it may also act as a go/no go door.

During the first stages of a project, there is much uncertainty about the project’s real impacts and, as a result, about the real net social benefits. As time elapses, there is more knowledge about the impacts, which lead to better estimates of the net project benefits. Thus, CBA studies carried out later can be more accurate. Consequently, ex post studies are generally more precise than in medias res studies, which, in turn, are also more precise than ex ante studies.

An in medias res analysis can also help in decision-making, on ongoing projects – in between incremental phases – when the decision maker may have second thoughts about the project. In between phases, it may be potentially feasible to allocate the resources involved to alternative uses. Given that an important share of the costs has already been incurred, and that the remaining benefits will usually outweigh the remaining costs, such analysis have rarely led to interruption or termination of the project nearing completion. However, Boardman (2001) indicates that this can happen. It cannot be overlooked that in the first place, the project itself was started on wrong premises, and that future decision makers have been correctly advised or have had time to examine the completed phases.

CBA may seem complex, but to help make the process more manageable, Table 11.14 elaborates the steps required to carry out a cost benefit analysis.
| Sr. No. | Steps                                                                 | Features                                                                                                                                                                                                 |
|--------|----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1      | Determine the project alternatives                                   | Altering two or three parameters/dimensions simultaneously greatly increases or decreases the number of alternatives.                                                                                     |
| 2      | Decide relevant costs and benefits                                    | The analyst must consider who has standing (*locus standi*), that is, whose benefits and costs should be assessed in the analysis.                                                                     |
| 3      | List down the impacts and select measurement indicators (units)       | The physical impacts of the different alternatives are listed either as benefits or costs as well as the units of measurement. The term *impacts* (cause-and-effect relationship) broadly includes inputs (required resources) and outputs that affect the utility of individuals with standing. Impacts not having any value to human beings are not considered. Some impacts cannot be measured using natural measurement units, in which case, some indicators (with, of course, some loss of information) are used. |
| 4      | Forecast the impacts quantitatively over the project life span        | Project impacts usually extend over time. Although these impacts should to be quantified, it is usually difficult to do so.                                                                                 |
| 5      | Monetize (attach dollar values to) all impacts                        | Each impact is given a value in dollars, more specifically, the time saved, lives saved, and accidents avoided. Environmental impacts are difficult to evaluate. In CBA, value is assessed from willingness-to-pay, can be determined from the appropriate demand curve – when markets exist and work well. Naturally, problems crop up when markets are inexistense or do not work well. If nobody is willing to pay a strictly positive sum for some impact, then, in that CBA, that impact would have zero value. |
| 6      | Benefits and costs are discounted to obtain present values            | Money obtained in the future does not hold the same value to a person holding the money now, at present. *Discounting* is a method of converting money obtained in the future to present day values. Therefore, project costs or benefits that arise in the future need to be discounted. Discounting is not related to inflation *per se*, although inflation must be considered. |
| 7      | Calculate the net present value (NPV) of each alternative             | The *net present value* \( NPV = PV(B) - PB(C) \) of a project alternative, is the difference between the present value of the benefits and the present value of the costs. The project with the largest NPV has the largest present value of the net social benefits. |
| 8      | Perform sensitivity analysis                                          | The NPV obtained above depends on the predicted impacts and their monetary valuation. Very often,                                                                                                              |
11.5 Using Cost Benefit Analysis for Resilience

Table 11.14 (continued)

| Sr. No. | Steps                                                                 | Features                                                                 |
|---------|----------------------------------------------------------------------|--------------------------------------------------------------------------|
| 9       | Produce recommendations based on the $NPV$ and sensitivity analysis   | The project alternative with the largest $NPV$ is deemed to be the best. However, the sensitivity analysis might suggest otherwise. Analysts produce recommendations, but do not take decisions. |

11.5.2 The Actors

Persons associated in the decision making process may be divided into three types:

**Analyst**: Looking in the right perspective

**Guardian**: Auditor, shopkeeper = one cent is one cent

**Spender**: Consumer society = why bother to save if one can spend?

While the analyst is expected to do the right thing through a proper and objective analysis, Boardman (2001) explains that this is not always easy, as the reports somehow may get contaminated with the views of two types of people: the guardians and the spenders, who are caricatured below.

**Guardians**

Guardians are people working in central budgetary agencies, and/or hold accounting posts within line agencies. They tend to be obsessed with a bottom-line budgetary orientation. They naturally tend to equate benefits with revenue flowing into their organisation or other governmental coffers and to associate costs with revenue flowing out from their organisation or other governmental coffers. They generally wish to use a high social discount rate. Either due to their agency’s culture or their financial education, their natural preference goes to a financial market discount rate, which is usually higher than the relevant or corresponding social discount rate. They are well aware that high discount rates will render most projects quite difficult to justify because costs usually occur before benefits (whose discounted values decrease rapidly, with higher discount rates). Thus, it is easier to reduce the number of spenders who, most likely, underestimate costs, overestimate benefits, and generally spend money less efficiently than the private sector. In that sense, they are truly the watchdog (guardians) of the coffers.
Spenders usually work in line or service departments. Whereas some service departments are involved with physical projects, such as transport, other social service departments (welfare, health, or recreation), need to invest in human capital.

When they spend money on constituents, spenders tend to consider such expenditure as benefits rather than count it as costs. Thus, expenditure on labour is considered as a benefit instead of a cost. Spendersons view themselves as builders or professional distributors of services provided by government.

However, for the spenders, the money paid by government to construction workers building the highway is also a benefit. Thus, spenders consider both project benefits and project costs as benefits.

Sometimes no project is better than spending money on a useless project. However, spenders prefer to support any project alternative instead of the status quo (no project). It is, therefore, perfectly understandable that guardians do not trust spenders. They most often oppose each other.

Usually, politicians give preference to projects that shower benefits on specific interest groups, while spreading costs widely over the population or camouflaging them behind other expenses. Spendersons think similarly. A weightage is given to each impact category, depending on the strength of the link that constituents associate between their agency and the impact. They concentrate on impacts for which they will receive plenty of credit from their constituents, and will blindly ignore others. It is human nature to notice expenditure on oneself. Thus, such “benefits” are usually weighted more heavily than social benefits. For example, construction jobs are given a higher weightage than diffuse social benefits. So, efforts towards resilience might not receive a due significant weightage.

Spenders also behave similarly to politicians – who insist on completing partially completed projects – in trying to push for large, irreversible projects requiring capital-intensive resources. Thus, urban rail systems will get a preference over buses, because once the infrastructure is installed, it is difficult to redeploy it to alternative uses. Therefore, the system is bound to remain in operation, while constituents are guaranteed to obtain some benefits. Furthermore, if as usual, such projects have lower operating costs, permitting lower tariffs, this ensures significantly high usage levels, and hence increasing constituency support further.

It would seem that spenders do not really understand how markets work. They believe that markets are quite inefficient, believing unemployment exists in all sectors of the economy, which will therefore be decreased by the number of people employed on a government project. However, when workers from a sector or industry A move to a government job, there are vacancies in sector A. These vacancies have now to be filled, either by unemployed people (there has been a job creation) or by workers from a sector B, where other vacancies are now created. Spendersons do not understand that project resources have been diverted from other potentially productive sectors that also involve jobs.

Furthermore, spenders believe in a multiplier effect between job creation and other project expenditures. At the extreme, there is a belief that expenditures (costs) are “benefits”, which multiplied by the multiplier, enable any government project to produce other large “benefits” bigger than “costs”.

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Spenders generally prefer to use a low (even zero) social discount rate, for two reasons: (1) some are not familiar with the discounting concept (2) others are aware that such practice will increase the project’s NPV and, therefore, raise the probability of its implementation. As mentioned earlier, spenders also like to underestimate costs, and overestimate benefits, either on purpose or because they are unduly optimistic.

11.5.3 CoBAYe

CoBAYe (Cost-Benefit Analysis under interdependencY and uncertainty) is a decision-making tool, developed by Proag (2015), aimed to help the public decision makers (or private) who must take a group decision within a given territory. Using the Cost-Benefit Analysis (CBA) as a starting point, the tool overcomes some of its limits and proposes an (1) ex-ante (2) concomitant (3) or ex-post evaluation method for a project (public or private), thus giving more information to the decision maker and therefore helping him in his choice to decide respectively (a) implementation of the project (b) possible concomitant installations of the extension or the renewal of the project, for example. (Proag and Proag 2015a, b, c).

11.5.4 Resilience

As explained earlier (para. 11.1.4), a system is usually designed to behave in a certain way under normal circumstances. When disturbed from equilibrium by a disruptive event, the performance of the system will deviate from its design level. The resilience of the system is its ability to reduce both the magnitude and duration of the deviation as efficiently as possible to its usual targeted system performance levels.

Of course, the system may be lacking resilience completely, or acquires some (or complete) resilience with some background support, resting on works needing heavy investment.

To give an example, resilience for a house located in a flood prone area lies between two extremes: (1) flooding each time it rains (2) never being flooded. Against these two extremes, the analyst may find it difficult to decide whether it is acceptable for one’s house to get flooded every 10 years, or every 30 years. Or never at all during one’s lifetime? The three alternatives will need adequately designed drains of different sizes and costs.

Once the users understand and accept the different safety levels from floods – through legislation, preferably – it would not be difficult for the analyst to determine the cost of providing the different acceptable levels of possible protection or the necessary resilience. The stakeholders would then have the facts (protection levels, costs) to decide on their willingness to invest in such or other form of protection.

Experience makes us wiser, but how many countries are prepared or ready to consider resilience against a future pandemic as COVID-19?
11.6  Case Study: Resilience in a Water Supply Network

11.6.1  Vulnerability in the System

A water network is an important infrastructure service provided to consumers. However, it is vulnerable, because a combination of several factors as indicated in Table 11.15, may prevent the network from giving a satisfactory performance.

Surface water is stored in manmade impounding reservoirs, which, often, have a capacity barely beyond a year’s supply. It is rare that heavy rains occur throughout the year, to keep the impounding reservoir continuously full. When rainfall does occur abundantly, or if the season is quite a rainy one, the reservoirs are quickly replenished so that supplies may sometimes be adequate to last more than 12 months. However, this also turns into a vulnerable situation as an overflowing impounding reservoir, very often, entails premature over consumption.

11.6.2  Remedial Measures

After examination of the factors mentioned in Table 11.15, it may be observed that resilience improvement can take place by manipulating different parameters, as shown in Table 11.16.

Table 11.15  Vulnerability parameters to be considered

| Variables | Dependents | Vulnerability parameters |
|-----------|------------|--------------------------|
| A         | Resources  | Climatic factors         |
|           |            | Drought                  |
|           |            | Heavy rainfall           |
|           |            | Floods                   |
|           |            | Change in precipitation averages and extremes |
|           |            | Water quality            |
| B         | Infrastructure | Technology          |
|           |            | Impounding reservoir capacity |
|           |            | Service reservoir capacity |
|           |            | Treatment technology     |
|           |            | Electricity              |
|           |            | Manpower                 |
| C         | Network    | Age of network           |
|           |            | Pipe type (DI, uPVC, AC, HDPE, etc) |
|           |            | Reticulation (branch, grid and loop system) |
|           |            | Physical losses          |
|           |            | Pilferage                |
|           |            | Pressure inadequacy      |
| D         | Use        | Demand v/s supply        |
|           |            | Forward planning         |
|           |            | Water management strategies |
|           |            | Political influence      |
In Mauritius, the water supply network consists of both surface water sources (rivers, impounding reservoirs) and groundwater sources. A groundwater source requires digging a borehole and then installing a submersible pump to pump the water into a reservoir, sometimes followed by a booster pump as in Figure 9.1. With a simple basic arrangement, one pump ran continuously for 17 years before it broke down. When that happened, the Central Water Authority (CWA), Mauritius was lucky to obtain and fix another submersible pump, after first removing the initial pump. During the repair works (fortunately, only one day), water had to be supplied by tanker lorries and other means. Over the years, the CWA has come up with several approaches to increase the resilience of the water supply network, such as:

(a) Dig a second borehole
(b) Intensive pumping during heavy rains
(c) Install a standby generator in case of power breakdown
(d) Interconnect different networks

(a) Having a second borehole provides two advantages: (1) in Mauritius, groundwater levels in the aquifer do vary widely – as much as 20 metres – between the dry and wet seasons. Therefore, the two pumps may be selected to operate more efficiently, one at the dry season level, and the other at the wet season level, and (2) should there be a pump breakdown as in the incident above or scheduled maintenance works, an immediate relief is available with the second borehole, even if the pump works less efficiently during a short time.

(b) Intensive pumping during heavy rains: Surface water is impounded within man made reservoirs, which barely have a capacity beyond a year’s supply, unless

Table 11.16 Characteristics which influence resilience

| Characteristic               | Wrtevent | Reason                                                                 |
|-----------------------------|----------|------------------------------------------------------------------------|
| Robustness                  | Ex-ante  | In the retrofit or design stage, infrastructure resistance to extreme events or impacts needs to be upgraded or increased. |
| Redundancy                  | Ex-ante  | In the retrofit or design stage, when options to increase robustness may be more expensive than options to increase redundancy. |
| Reliability                 | Ex-ante  | In the retrofit or design stage, the infrastructure (pipes, pumps, etc.) should be reliable under all conditions, even extreme events. |
| Resourcefulness             | Ex-ante  | Prior to a hurricane, preparedness and organisation to restore infrastructure service performance will increase resourcefulness. |
|                             | Ex-post  | Resourcefulness will be subject to decisions taken to restore infrastructure performance. (e.g., how available resources – post-disaster – are distributed, and priorities established). |
| Rapidity (Response and recovery) | Ex-ante | Design changes, preparedness and organisation to restore infrastructure service performance, prior to a hurricane (event), will increase rapidity. |
|                             | Ex-post  | Rapidity will be subject to decisions taken to overcome disruption and to restore infrastructure performance (e.g., how available resources – post-disaster – are distributed, and priorities established). |

11.6.3 Resilience Features in the Water Supply System

In Mauritius, the water supply network consists of both surface water sources (rivers, impounding reservoirs) and groundwater sources. A groundwater source requires digging a borehole and then installing a submersible pump to pump the water into a reservoir, sometimes followed by a booster pump as in Figure 9.1. With a simple basic arrangement, one pump ran continuously for 17 years before it broke down. When that happened, the Central Water Authority (CWA), Mauritius was lucky to obtain and fix another submersible pump, after first removing the initial pump. During the repair works (fortunately, only one day), water had to be supplied by tanker lorries and other means. Over the years, the CWA has come up with several approaches to increase the resilience of the water supply network, such as:

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(b) Intensive pumping during heavy rains: Surface water is impounded within man made reservoirs, which barely have a capacity beyond a year’s supply, unless
there are additional heavy rains during the year. The same heavy rains also recharge the aquifers. Unless pumping is carried out, the ground water will certainly travel towards the sea. One idea has been to carry out intensive pumping during the rainy period. This enables extracting a maximum amount of water from underground. As the consumer receives water from the network, less water needs to be extracted from the reservoirs. This leads to saving the equivalent amount of water in the reservoirs.

(c) Installing a standby generator, with an automatic start in case of electricity supply breakdown increases the resilience of the network. Without a generator, the pumping operation is completely dependent on availability of electricity from the grid. With the standby generator, as soon as there is a power cut, the generator comes into operation (sometimes, there is a waiting time of a few minutes, in case the grid comes on again) thus powering the pump. Even when the grid comes again into operation, the generator keeps running for some 10-15 min, in case there is a grid power cut again. One precaution to be taken is to keep the fuel tank of the generator always full. It would be foolish to have a standby generator, with an empty fuel tank. This is part of the regular maintenance exercise (see also Chap. 20).

(d) Interconnecting different networks: For geographical and historical reasons, the water supply network developed into several independent sub-networks or systems. However, droughts in the past have driven home the necessity of possible interconnections. Gradually, a few interconnections have been made, so that should a water system be subject to a reduced supply for various reasons, there is a possibility of mitigating the shortfall through a connection from another system.

Thus, the overall water network has acquired a certain degree of increased resilience which helps in supplying water to the consumers satisfactorily during the whole year.

Figure 11.8 shows some of the details of such a system.

Table 11.17 summarises the different approaches developed in the water supply system.

![Fig. 11.8 Adding resilience to the water system](image)
The different forms of resilience explained above have a cost. For example,

(1) During the 1999–2000 drought, the cost of providing water tanker service and other facilities, amounted to some Rs. 50 million (2.5 million Euros, at that time).

(2) The pipe linking Mare Longue reservoir to La Marie filters cost Rs. 50 million (1.25 million Euros, at the 2018 exchange rate), for an addition of 20,000 m$^3$/d, which is no longer available for hydropower and irrigation.

(3) The pipe connecting Midlands reservoir and Piton du Milieu reservoir is estimated at a cost of Rs. 400 million (10 million Euros, at the 2015 exchange rate), for an addition of 20,000 m$^3$/d.

These figures may be compared to an average selling price of water of Rs. 9/m$^3$, for a total annual sold volume of about 90 Mm$^3$. A cost benefit analysis could be carried out to assess the feasibility of adding such resilience. Interestingly, when it comes to water, is there an option of doing without (resilience or water)?

| Table 11.17 Adding resilience to the water supply network of Mauritius |
|-------------------------------------------------------------|
| Robustness | Redundancy | Reliability | Resourcefulness | Response after event |
| Surface water/ground water conjunctive use | ♦ | ♦ | ♦ | ♦ |
| Double borehole | ♦ | ♦ | ♦ | |
| Standby generator | ♦ | ♦ | ♦ | |
| System interconnection | ♦ | ♦ | ♦ | ♦ |
| River (surface) pump | ♦ | ♦ | ♦ | ♦ |
| Water rights use during drought | ♦ | ♦ | ♦ | ♦ |
| Tanker service during drought | ♦ | ♦ | ♦ | ♦ |
| New impounding reservoirs | ♦ | ♦ | ♦ | ♦ |
| New service reservoirs | ♦ | ♦ | ♦ | ♦ |
| Local/domestic storage tanks | ♦ | ♦ | ♦ | ♦ |
| New treatment plants | ♦ | ♦ | ♦ | ♦ |

### 11.6.4 Cost of Providing Resilience

The different forms of resilience explained above have a cost. For example,

(1) During the 1999–2000 drought, the cost of providing water tanker service and other facilities, amounted to some Rs. 50 million (2.5 million Euros, at that time).

(2) The pipe linking Mare Longue reservoir to La Marie filters cost Rs. 50 million (1.25 million Euros, at the 2018 exchange rate), for an addition of 20,000 m$^3$/d, which is no longer available for hydropower and irrigation.

(3) The pipe connecting Midlands reservoir and Piton du Milieu reservoir is estimated at a cost of Rs. 400 million (10 million Euros, at the 2015 exchange rate), for an addition of 20,000 m$^3$/d.
11.7 Conclusion

The concept of vulnerability implies a measure of risk associated with the physical, social and economic aspects and implications resulting from the system’s ability to cope with the resulting event. Resilience implies the ability of a system to perform properly even when placed under pressure or the ability of systems to absorb and recover from the impact of disruptive events without fundamental changes in function or structure.

Based on what is required to face disasters, features should be inbuilt in the system (design, normal operation, etc) so as to offer better, if not complete, resilience to the system. As resilience increases, the degree of damage for a given intensity hazard decreases.

Measuring resilience is not easy as this depends on the system under study. It is important to look at the ways resilience is being considered and use these as a method to measure resilience, either qualitatively and quantitatively.

In most cases, the systems are rarely totally down. While qualitative assessment is useful to understand how bad things are, quantitative measures give quantified estimates of performance, time and effort (cost) that are more meaningful to stakeholders.

System resilience is concerned with the protection of vulnerable people, and probably poor as well. Providing resilience means providing a safeguard against a certain risk. Hazards are more severe when the return period is a longer one. The important issue relates to the level of protection that is considered desirable.

For example, rainfall frequency and intensity records can be used to estimate the magnitude of rains and the ensuing flood flows. In this respect, it is important to note that there is a 26% probability that a 100 year rain will occur during the next 30 years (a generation).

In practical terms, this means that each generation has a 1 in 4 chance of experiencing flooding, even if an exceptional rainfall intensity of 100 year has been considered. Over a 75 year lifetime, the likelihood rises to 0.53, i.e., the average person has a 1 in 2 chance of experiencing flooding during his lifetime.

Is the population ready to accept this? If no, what is the price to pay to have a safer protection?

The issue of event probability also means that one thing is certain – the cost of expenditure incurred, with possible benefits, in the way of cost avoidance, should the disaster event eventually occur.

The development of the water supply network in a haphazard way brought inherent vulnerabilities, which need to be removed gradually. Some resilience has gradually been introduced into the system, sometimes at high cost. A cost benefit exercise could be carried out to determine the feasibility of adding such resilience.

Measuring resilience is not easy as this depends on the system under study. It is important to look at the ways resilience is being considered and use these as a method to measure resilience, either qualitatively and quantitatively.
In most cases, the systems are rarely totally down. While qualitative assessment is useful to understand how bad things are, quantitative measures give quantified estimates of performance, time and effort (cost) that are more meaningful to stakeholders.

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