Adaptive Capacity: Electric Power Restoration in New York City following the 11 September 2001 Attacks

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Abstract. The 2001 World Trade Center attack resulted in widespread and highly non-routine failures to critical infrastructure systems. An immediate priority following the attack was the restoration of electric power in lower Manhattan. A study of the organization responsible for conducting this restoration is here presented in order to build theory about organizational characteristics that contribute to resilience. Data sources include logs of the behavior of the electric power infrastructure as well as responses to questionnaires given to various levels of personnel. An additional layer of depth is achieved by investigating cognitive and behavioral activities underlying key tasks during power restoration, as collected through in-depth interviews with numerous personnel. In addition to identifying factors contributing to resilience, the study discusses how tradeoffs were made by decision makers on the way to making the critical decision about how to conduct restoration. The conclusions of the analysis are used to frame a refined set of properties of resilient organizations, and to provide observations on the processes that underlie how organizations achieve (or fail to achieve) the potential for resilience.

1 OVERVIEW

This paper uses a case study approach to describe cognitive and work processes underlying a number of factors that are thought to contribute to resilience. The case study concerns the response of New York City's main electric power provider to the power outages induced by the 11 September 2001 attacks. An analysis of numerous data sets collected in the months following the attack is used to consider whether and how these factors figure into the case. The conclusions of the analysis are used to frame a refined set of questions on the cognitive processes that underlie how organizations achieve (or fail to achieve) the potential for resilience.

The result of this work is intended to be greater clarity in describing whether and how buffering capacity, flexibility/stiffness, margin, tolerate and cross-scale interactions contribute to the potential for resilience. The particular contribution of this work is in describing the cognition of decision makers at various levels in the organization both in engineering the values of these factors and in managing the tradeoffs among them.

2 BACKGROUND

Among the definitions of resilience are an ability to resist disorder (Fiksel 2003), as well as an ability to retain control, to continue and to rebuild (Hollnagel and Woods 2006). Yet resilience may be a difficult concept to measure. Indeed, as a system is performing it may be possible only to measure its potential for resilience, rather than its resilience *per se* (Woods 2006). The following factors are thought to contribute to resilience (Woods 2006):

- **buffering capacity**: size or kind of disruption that can be absorbed/adapted to without fundamental breakdown in system performance/structure
- **flexibility/stiffness**: system's ability to restructure itself in response to external changes/pressure
- **margin**: performance relative to some boundary
- **tolerance**: behavior in proximity to some boundary
- **cross-scale interactions**: how context leads to (local) problem solving; how local adaptations can influence strategic goals/interactions

Resilience engineering is "concerned with monitoring and managing performance at the boundaries of competence under changing demands" (Hollnagel and Woods 2006). In seeking to engineer resilience, it is therefore appropriate to consider how these factors may be measured, and whether they are reflected in studies of organizations that have demonstrated a potential for resilience through their actions. Further examination of these actions ought to uncover the cognitive and behavioral processes that underlie and enable resilience.

It is first appropriate to consider whether resilience should be studied in the context of extreme events. There are some immediately obvious reasons that it should be. Performance of organizations in responding to extreme events is often at the boundary of their experience. It is conducted by skilled individuals and organizations, who must make high-stakes decisions under time constraint (Mendonça forthcoming). On the other hand, the boundaries of experience may be difficult to identify *a priori* (i.e., before the event has occurred) and perhaps even afterwards. It is very likely that unskilled individuals and organizations will participate in the response. The decisions taken during the response may be very difficult to evaluate, even after the event. Finally, the long lag times between events—coupled with the difficulties involved in predicting the location of events—can make pre-event monitoring impractical and perhaps impossible. Many of these properties of extreme events are revisited in the following case study.

3 CASE STUDY

The 2001 World Trade Center (WTC) attack resulted in loss of life and in considerable damage to the built environment of New York City. Indeed, due to the location of the Twin Towers, their collapse resulted in massive disruptions to critical infrastructure systems such as emergency services, electric power, telecommunications and transportation

(O'Rourke et al. 2003). Further examination of the patterns of disruption clearly shows that these infrastructures were highly interconnected (or interdependent), both by design and as a result of changes induced by the event (Mendonça and Wallace forthcoming-b).

This case study concerns the restoration of the electric power system in the two to three weeks following the WTC attack. Damage to the electric power system was considerable, certainly beyond what had been experienced in prior events. This included the loss of 400 mega-watts (MW) of capacity from two substations which were destroyed following the collapse of World Trade Center building 7, and severe damage to five of the feeders that distributed power to the power networks. Indeed, five of the eight total electric power distribution networks in Manhattan were left without power. In total, about 13,000 customers were left without power as a result of this damage. An immediate priority for the city (and, in the case of the New York Stock Exchange, the nation) was to restore this power as quickly as possible. As discussed in the remainder of this paper, the company responsible for providing electric power engaged in two inter-related strategies for restoring that power: connecting trailer-mounted portable generators to provide spot power; and installing temporary feeder lines—called shunts—to connect live networks to dead ones.

3.1 Method

For the current study, initial consultations with the company were done in order to identify critical incidents, particularly those which involved highly non-routine responses (e.g., those which were improvised). This led to a set of eight incidents. For each incident, interviews were conducted with personnel who were involved at various levels and capacities in the response (e.g., line personnel through senior vice presidents). Respondents were asked to come prepared to discuss the incident, and to bring any necessary supplementary materials (e.g., maps, drawings). With a few exceptions, the critical decision method (Flanagan 1954; Klein et al. 1989) was used for all interviews, with two interviewers and one or two respondents. One interviewer asked the probe questions (Klein et al. 1989); a second took notes. With one exception, it was not possible to audio- or video-record the interviews. Following the interview, participants filled out a brief questionnaire on their background and experience in responding to the incident. Finally, data were collected on the performance of technological systems (e.g., timing and location of restoration of incremental power capacity), supplemented with secondary sources such as newspaper and internal company reports.

Details on two critical decisions (i.e., using trailer-mounted portable generators and installing shunts—or temporary lines—to restore capacity) are presented and discussed here in order to evaluate the sufficiency and completeness of the set of factors thought to create the potential for resilience. Cognitive and behavioral processes underlying the response are identified. The conclusions of the analysis are then used to frame and define a refined set of factors, and to raise questions on the cognitive processes that underlie how organizations achieve (or fail to achieve) the potential for resilience.

3.2 Restoration through Addition of Generator Capacity

Soon after the attack, the company began attempting to procure trailer-mounted generators (see Figure 1) in order to provide spot power to critical customers. By 12 September, it was clear that the amount of time and effort required to secure, install and operate these generators would be considerable. As a result, the company decided to create a Generator Group, comprised of individuals from various parts of the organization, which would have primary responsibility for work in this area. Procedures implemented by the group included tracking the status of generator orders, installations and refueling, as well as decommissioning the generators. Each generator was assigned a unique identifier, and the time at which it was connected to a critical customer load was logged, as was the time that the customer was restored to the network. Tools used by the generator group to accomplish these procedures included telephones, system maps and databases. The databases (both paper and electronic) could be used to determine the status of work on each generator, as well as whether the generator was currently energized (i.e., providing power to the customer).

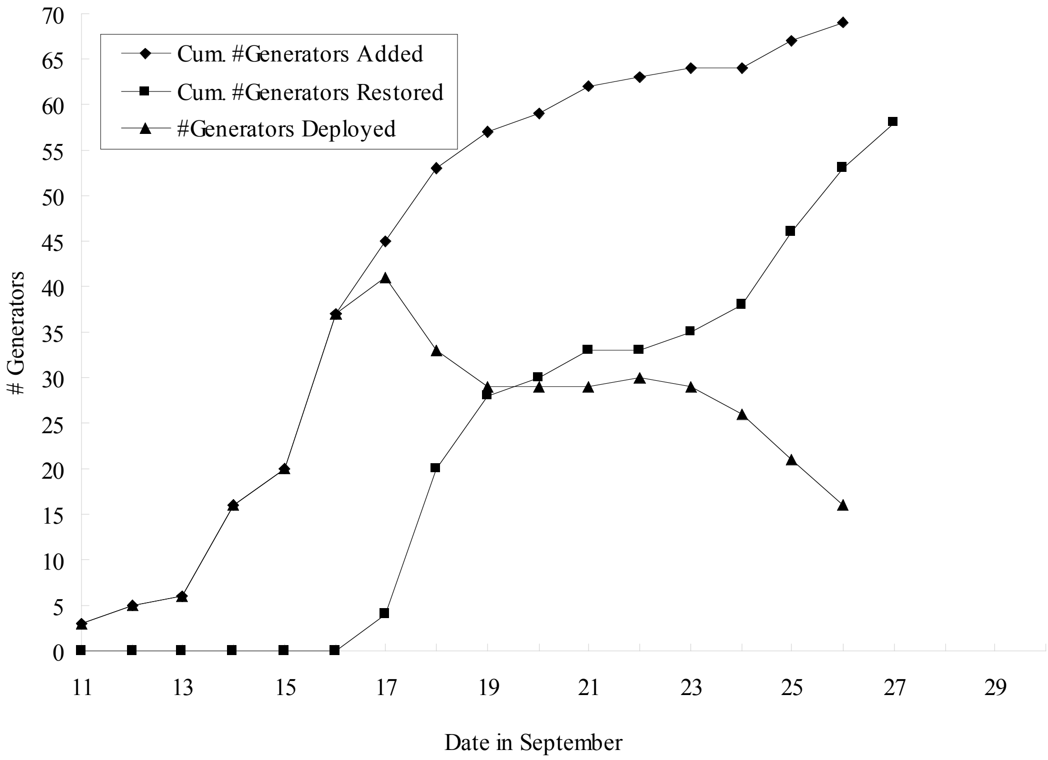

Fig. 1. Use of Generators for Power Restoration. The figure shows three cumulative totals from 11 to 27 September: number of generators added, number of generators restored to the network, and number of generators deployed.

By examining the database used to log the status of generator installations, it is possible to describe three aspects of this component of the restoration. The number of generators deployed to the field over time indicates the amount of activity in using generators (as opposed to shunts) to supply power over time. As shown in Figure 2, deployment of generators began on 11 September. The number of units deployed rose steadily until 16 September, then declined steadily, reflecting a shift in load to shunts, as discussed below. The cumulative number of generators added to the system shows the extent of generator use throughout the study period. It should be emphasized that generators were a shorter-term solution to the power restoration problem. The medium-term strategy was the use of temporary shunts (with the longer-term strategy the return of all customers to the permanent network). The final data series in Figure 2 (cumulative number of generators restored) shows that, until 16 September, all field generators were in use (i.e., none of the customers using those generators had been restored to the network). As of 28 September, customers on nearly all generators for which sufficient data are available were restored to the network. On 29 September, the Generator Group was disbanded.

3.3 Discussion Part 1

The *buffering capacity* of the company with respect to required generating capacity provided by generators appears to have been essentially unlimited. Generators were readily available from nearby sources (such as the companies that manufacture these generators). Fuel sources were also identified, but for a brief time could not be brought speedily into Manhattan: there were numerous questions at the bridges and tunnels that border Manhattan about the sufficiency of truck drivers' credentials, and as a result many fuel trucks could not cross over to the island. Higher-level discussions between the states of New York and New Jersey ultimately resulted in the trucks being able to enter Manhattan. A second observation regarding buffering capacity is that generators were clearly seen as a short-term solution to the power restoration problem. As will be discussed in the second half of the case, this is an example of how buffering capacity may be distributed across different parts of the organization.

The nature of *flexibility/stiffness* in the company is suggested by its decision to create a new organizational structure—the Generator Group—almost immediately after the attack in order to manage generator procurement and use. The group was dissolved once the generators ceased to be a crucial part of the restoration plan. In other interviews (not discussed here), respondents stated that some existing organizational units improvised their roles, undertaking tasks that were within the capability of the organization but which were not in the usual range of activities for the units themselves. This phenomenon has been amply demonstrated in the response to many other events (Webb 2004).

The *cross-scale interactions* of the company involved boundary restructuring with respect to other organizations such as police departments (as mentioned previously), as well as to others not discussed in detail here. For example, the Federal Emergency Management Agency on at least one occasion appropriated materials intended for use in power restoration activities, requiring re-planning by the company. This and the police department case mentioned previously help extend the range of interactions induced by context: in both cases, changes in context led to strategic-level interactions—as opposed to local problem solving—in which higher-level personnel interacted to solve problems which had materialized at lower levels in the organizational hierarchy. Finally, it should be noted that the company developed new relationships with some of the suppliers of the generators (a task undertaken by the Generator Group), again highlighting the importance of cross-organizational interactions, not merely those within the company itself, as relevant to resiliency.

As with other extreme events, the *margin* and *tolerance* are difficult to evaluate for this case. In fact, a key observation from the case as thus far described is that the magnitude of the restoration problem far exceeded that of previous experience. Indeed, while generators had been part of previous restorations, the company had never before needed this quantity in such a short time. Using the available data, it does appear that the path to restoration—as indicated by the cumulative number of generators restored to the network (see Figure 1)—followed an *S*-shape, similar to that of a prototypical learning curve. Because the generator and shunting strategies were complementary, this curve will be revisited in the next section.

3.4 Restoration through Addition of Distribution Capacity

The second broad strategy for lower Manhattan power restoration was the use of shunts—cables with 13 kilovolt (kv) capacity—which were used to make connections between dead networks and live ones. This task was handled by existing units in the organization (such as Distribution Engineering and Electric Operations). Procedures executed by these units included determining shunt routes through the city and coordinating pick-ups (i.e., the actual connecting of the shunts to the networks). Tools used for these procedures included maps of the system (many of which had to be changed to reflect current field conditions), engineering drawings, databases, telephone and mathematical models of the electric power system. One of the databases was used to track the status of work in connecting the live network (called the feeder) to the dead one (called the destination). It specified the date and time when work was begun and completed, and included the total duration of the work along with the capacity of the shunt (i.e., 13kv). It was therefore possible to check the status of this work on the system.

A summary of restoration efforts with respect to shunt connections is given in Figure 2. The cumulative total number of connections by day shows a path to restoration that should be viewed in relation to the path to restoration for capacity added by generators as given in Figure 1. In this situation, however, the path to restoration is very nearly linear, in contrast to the *S*-shaped path in Figure 1.

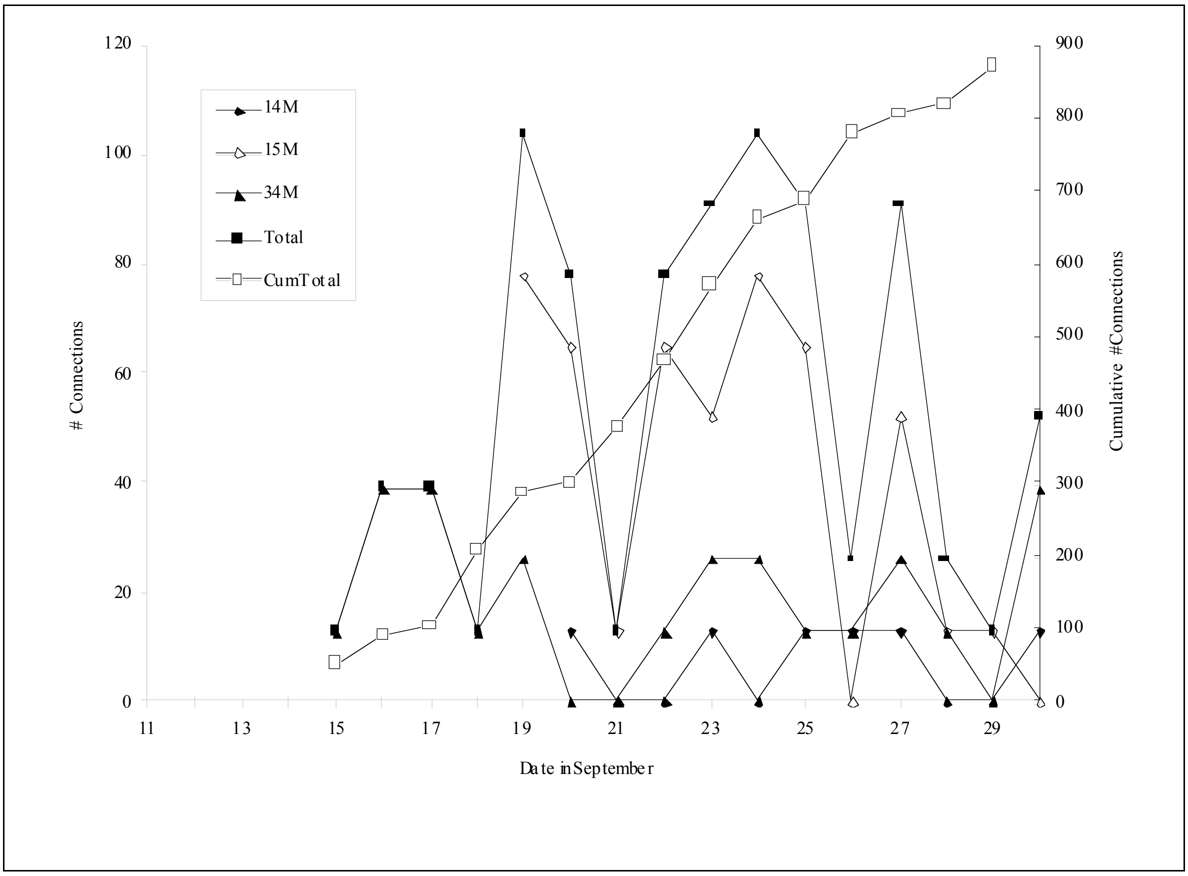

Fig. 2. Use of Feeders for Additional Capacity. The figure shows the number of connections made per day from three live networks (14M, 15M and 34M), as well as the total number of connections per day and the cumulative total of connections by day.

The results of an interview with two of the personnel involved in implementing the shunting plan illustrate some of the cognitive- and behavioral-level issues relevant to engineering resilience. The two individuals were closely involved with the field operations, supervising and undertaking a number of activities. The shunting activities brought them in close proximity to Ground Zero, and thus close to the rescue and debris removal activities being conducted there. In the days following the attack, there were often concerns about the collapse of the slurry wall bordering the site (Mendonça et al. 2005) or the collapse of buildings on-site. One of the individuals noted " I mean there was tons of people coming in and out, while we were laying these shunts I mean they'll be blowing the horn a building possible danger of collapse, then all the sudden you got a wave of people running towards you to get out so now your gotta get your people out of there too. This was constantly going on. Back and forth and all." Similarly, there were negotiations with the police department and other organizations about use of the roadway, with company crews sometimes needing to yield to other workers or vehicles. A final observation is that these and other conditions in the field required field personnel to communicate frequently with engineering operations, which would often result in plans needing to be redrawn. As stated by one of the individuals, "So they [engineering operations] were constantly looking at [the plan] to see how we can pick up as many feeders as possible."

3.5 Discussion Part 2

The *buffering capacity* of the company is reflected in the use of a larger number of shunts than in previous situations. A difference is that in previous situations shunts had not typically been lain in the street. Rather, they were routed below ground through manhole covers. Routing shunts through the street—which required boxing them in at curbside, and running them through trenches at intersections—made it possible to accomplish the job more quickly; however, this strategy also led to some complications in the field due to interactions with other organizations.

The *flexibility/stiffness* of the company is reflected mainly in the major restructuring of physical network, resulting in a new design for the distribution system (i.e., one using three larger networks instead of eight smaller ones). In contrast to the generator situation, there was no major restructuring of organizational units.

Margin and *tolerance* are again somewhat difficult to measure, for many of the same reasons cited previously. The path to restoration—as measured by the number of feeder connections made per day—suggests a straight path to achieving sufficient capacity in the medium-term. Other interviews not cited here also suggest that the loss of distribution capacity created opportunities in the longer-term for redesign of some aspects of the physical system (e.g., by reconsidering the placement of substations to replace those destroyed in the attack).

Cross-scale interactions are particularly evident here. As with many other disaster situations, there was short-circuiting of normal approval procedures, mainly to expedite work. Contextual factors (such as the physical condition of the built environment) led to some local problem solving, but also to local adaptations that influenced middle-level interactions (here, with engineering operations), rather than strategic-level ones. Finally, there were many examples of inter-organizational decision making, but also of negotiation, where goals conflicted across organizations (e.g., in determining how shared resources, such as the roadway network, were to be used).

CONCLUDING DISCUSSION

A case study approach has been used to examine the restoration of electric power in New York City by a single company following the 2001 World Trade Center attack. This approach suggests a number of revisions to the list of factors that may contribute to organizational resilience. *Buffering capacity* was highly relevant to this response. Yet large-scale emergencies may in fact yield buffering capacity with respect to materiel resources that is far beyond what is needed. Indeed, the materiel resources needed to execute the generator and shunting plans were requisitioned rapidly. The larger problem was how to organize these resources—in other words, how to exercise flexibility.

Evidence of *flexibility* is found in the company's efforts at revising organizational structure, but also its activities and which people are assigned to the activities. The design of the physical system may have helped determine the organizational structure, a question that might be further investigated through other studies of physical change in infrastructure systems. Finally, there is clearly much more work needed in understanding how decision strategies emerge in the emergency response environment (Mendonça and Wallace forthcoming-a). For example, in decision making under risk, a noncompensatory strategy tends to precede a compensatory one (Payne et al. 1993). It may be that contextual factors may help induce surprising patterns in choice of strategy (Chu and Spires 2003), particularly during extreme event decision making.

Throughout this case, *margin* and *tolerance* have been assessed according to the behavior of the physical system. Yet even with such assessments, it is difficult—perhaps even impossible—to evaluate performance on this case against some theoretical optimum. Even post-event, such assessments are challenging, leading to the use of measures of relative performance or efficiency, leading to the notion of efficient frontiers. Engineering estimates of anticipated system performance tend to be heavily informed by expert judgment rather than historical data (National Institute for Building Sciences 2001), and even these estimates are few. A further complication for this case in particular is that the path to restoration was almost certainly influenced by other organizations (e.g., time and effort were required to negotiate about the use of shared infrastructure systems).

An examination of *cross-scale interactions* in the case shows some evidence for a wider variety of interactions than thus far postulated (e.g., problem finding and solving may involve any combination of lower-, middle- and upper-level organizational units and personnel).

Taking a broader view of cross-scale interactions and other factors, a number of salient observations seem highly relevant to resilience but not reflected in the factors. Multiple organizations—as opposed to a single one—were involved in the company's response, and these were both *ad hoc* (e.g., equipment suppliers) and planned-for (e.g., customers with whom the company had to coordinate generator hookups). Second, there were multiple interrelated systems, each managed by their respective organizations, which had to make decisions or negotiate, particularly in situations involving shared, exclusive use or co-located resources. Third, at times there was considerable uncertainty about who controlled the system. This was evident in the difficulties with bringing fuel into Manhattan, the management of traffic in the field, and the evacuations of workers from Ground Zero. Finally, there was sometimes uncertainty about what comprised the system. In the case of the fuel supply, anticipated shipments could not be made. There was also a clearer case of equipment (a generator) which was requisitioned by another organization on its way into Manhattan. There are certainly many other such instances from this and other disasters.

All of these observations point to the importance of a new factor—*boundary-spanning capability*—in achieving resilience. Boundary-spanning capability refers to an organization's ability to communicate and make decisions with respect to collaborators or competitors. This capability differs from *margin* and *tolerance*, since it refers to activities that cross the boundaries between organizations, rather than those which require operating beyond performance boundaries. It is related to *cross-scale interactions*, but implies the notion that these interactions may take place across—and not merely within—organizations. The factor bears upon buffering capacity and flexibility, since an ability to span organizational boundaries may lead to changes in buffering capacity (as was the situation in the company's interactions with equipment suppliers, probably yielding improvements in this factor) and in flexibility (as was the situation in the company's interactions in the field regarding shared use of the roadway, probably yielding degradation in this factor).

In summary, then, this case study has yielded a number of refinements to the existing factors proposed by Woods and Hollnagel (2006), has revealed some practical difficulties with the assessment of these factors, and has resulted in the inclusion of a new factor—*boundary-spanning capability*—as a contributor to organizational resilience.

Acknwoledgements: This research was supported by US National Science Foundation grant CMS-0139306. The authors thank M. Crossan and F. Olivera for their valuable comments.

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