Modeling a National Power Crisis in Support of a Crisis Lifecycle Model

Eliot Rich

Leire Labaka,
Ana Lauge,
Josune Hernantes,
Jose M. Sarriegi

Finn Olav Sveen

University at Albany, SUNY
1400 Washington Avenue
Albany, NY 12222 USA
e.rich@albany.edu

Tecnun - University of Navarra
Paseo M. de Lardizabal nº13
20018 San Sebastian
SPAIN{llabaka, alauge, jhernantes, jmsarriegi}@tecnun.es

Prospectives Ltd Nuf,
Postsvingen 5A, N-3031
Drammen, Norway
and
NISlab, Gjøvik University College, 2802 Gjøvik, Norway
finn.olav@prospective.no

ABSTRACT

Society is dependent upon electricity. In the last decade international scale outages have occurred with unfortunate regularity. While the impact of these outages has been limited to a few hours or days, they have been expensive and prompted fears that more severe failures could occur. While crises are perceived as events, their true origins come from the pre-crisis and post-crisis phases, where preparations and learning set the stage for the successful management of unusual events. A power crisis of a few weeks duration can set the policy agenda for many years.

In this paper we describe a crisis model that captures the dynamic state of a power grid, the effects of failure on clients, government, and the public. The model was developed in concert with and validated by a panel of crisis managers. These factors combine to determine the post-crisis policies and socio-political factors that influence policy over much longer timeframes.

INTRODUCTION

Successful disaster mitigation requires extensive planning, logistical skills, and quickly deployable resources. Some events, such as hurricanes, occur with seasonal regularity. This consistency allows prediction and rehearsal of likely responses. Others, while seemingly triggered by unanticipated events, are rooted in or exacerbated by the context in which they occur. For example, prolonged hot or cold weather increases demand on power supplies and exposes vulnerabilities hidden by complex layers of technology, limited information, and conflicting customer requirements. Modeling the structure and context of these potential crises creates a platform for coordinated and more effective planning and training.

Planning for a large-scale disaster is particularly difficult, as solutions for localized problems do not scale linearly when extended to the national or international level. Failures and less severe but unintended consequences easily cascade across geographic, political, and organizational boundaries. For example, the ongoing problems in commissioning nuclear plants in Sweden have increased the cost of electricity in Norway, even though Norway uses its domestic hydro-electricity for almost all of its generation needs [1]. Overlapping areas of control and responsibility create confusion and inefficiency amongst responders. Variations in procedure among responding organizations limit their productivity. Prepared stocks of supplies may be insufficient, incompatible, or difficult to transport. Verification of disaster planning is expensive and often only tested through incomplete simulation. Unanticipated dependencies and constraints among elements of critical infrastructures slow action.

During the last decade there have been several large scale power cuts of international scale. Most notable are the 2003 blackouts in North America [2] and Italy [3, 4], and the 2003 blackout affecting Scandinavia, as well as the 2006 blackout in Europe which cascaded as far as Morocco [5]. Although perceived as severe crises, in reality the effects have been relatively benign, with power restored to the majority of subscribers within a few hours, and with almost all back online in a few days. Nevertheless, the crises were major disturbances which carried a high economic cost. It is prudent to ask the question "What would have happened if power generation facilities had been knocked out for a substantial amount of time?" More importantly, what can we do to prevent such crises?

In SEMPOC [1], a European Union funded research project, we work on such questions. Crises are often perceived to be unique, single events. However, most crises can be traced back to one or more properties of the socio-technical system. A power system is initially conceived, designed and then built. Over the course of its lifetime it receives many technical and organizational changes, such as those added in the last decades of deregulation or changes in the training of its operators. If the origins of crises are in the system itself, then the changes over the systems lifetime will also affect the likelihood and severity of crises. Furthermore, crises trigger changes in the system by prompting organizational and technical changes aimed at preventing or coping better with future occurrences. Thus we cannot take a single event view of a crisis; instead we have to view the crisis as having its own lifecycle which is closely connected to the evolution of the wider system.

In this paper we consider a power grid crisis that reaches the proportions of national concern. The resources and preparations for power restoration are important drivers of public anxiety, which in turn affects governmental action to maintain order and support the restoration and remediation efforts. Sample runs of the national model are presented below. The model is currently being calibrated for use as a policy tool. Ongoing research will move the boundary further to include international crisis and response.

The Crisis Life Cycle

Emergencies and crises are somewhat subjective terms. For example, a regional power outage is considered an emergency by customers requiring immediate remediation, and may invoke feelings of

[1]SEMPOC is funded by the European Commission - Directorate-General Justice, Freedom and Security, Prevention, Preparedness and Consequence Management of Terrorism and other Security Related Risks Programme. The SEMPOC project is described further at http://sempoc.eu

crisis. For the power company, however, the same event initiates a series of planned steps to restore service. This event becomes a power crisis only if the planned steps are insufficient to restore service before extensive damage ensues. A crisis is therefore a failed organizational response rather than an event [6]. Disasters and catastrophes reflect the scale of response and damage: A disaster ensures when an emergency exceeds the capacity of local responders. Catastrophes are large scale disasters.

A triggering event anchors the crisis timeline (Figure 1). The visibility of catastrophic events, such as the recent seismic events in Haiti and Chile, creates immediate demand for action. The timely provision of emergency relief – provision of food, shelter and medical needs – depends upon the quality of pre-crisis preparation. This preparation takes many forms, but its goals are the same: the knowledge needed to assess and prioritize needs, the availability of ready supplies and personnel resources, the logistical skills to deploy them, and the leadership required to set priorities amongst competing demands. Pre-crisis planning is a continuous process, with testing, revision, and review.

The post-crisis phase includes the activities needed to recover the pre-crisis state, replenishment of depleted stocks, and a review of the successes and failures during the crisis. In the wake of disaster, this phase can last decades, with severe economic and demographic effects. An early analysis of the Katrina response suggested that while the crisis and mitigation period lasted six weeks, reconstruction would

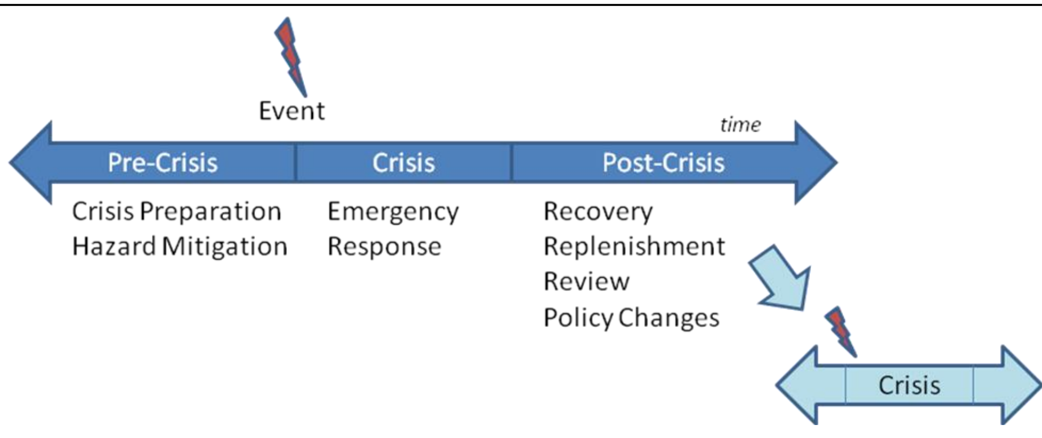

Figure 1: Crisis timeline

likely take well over a decade to complete [7]. Haiti may never recover fully from the 2010 earthquake, where 220,000 people lost their lives, millions were displaced from their homes, and untold billions of dollars lost.

Uncovering influences on national crisis dynamics

While events are precipitous, crises are not. The efficacy of the response to a national-scale event depends on the ability to predict event arrivals, mitigate possible points of failure, and the adequacy of preparation. These are in turn based on prior events, a cycle that continues backwards in time. As Coombs [8] puts it, "a crisis does not just happen, it evolves". The notion of a crisis life cycle leads to consideration of how the resolution of a crisis is affected by the structures that exist before the crisis and the range of actions available once the crisis occurs.

The structure of national infrastructure crises

National-scale crises are created in part through interdependencies among physical, economic, and socio-political infrastructures that exist before the crisis starts. While infrastructure size does not always imply interdependency (the Internet is a prominent counter- example), a combination of size and tight coupling of interdependent components increases the speed of failure cascades across regional borders [9, 10].

Physical interdependencies within the same infrastructure are common but not always apparent until failure. The systems that link power distribution networks also contain protection devices that open circuits and prevent overloading. A sagging power line hitting a tree branch in Ohio was the root cause of the 2003 blackout across the northeastern US [2]. Stefanini and Masera [11] trace the increasing frequency of power failures to information gaps between transmission systems and ICT control systems. We have become more efficient by consolidating our technology and automating our decision analysis, but at the cost of the resiliency provided by redundancy [10].

National economic systems are increasingly interdependent as well. Recent political quarrels between Russia and the Ukraine over the control of natural gas pipelines disrupted supplies to the EU, introducing a wide range of political and social pressures in the region [12]. The continuing internationalization of supply chains and reduction of locally stored inventories increases the need for reliability. Increasing inventories during times of tension requires the existence of storage facilities that take years to develop or in the case of electricity, do not exist. Pre-crisis planning may have to focus reduction of consumption rather than replacement, creating additional social conflict.

The role of socio-political forces

Mitigating the hazards and protecting against imbalances that create vulnerability to unexpected events is an important pre-crisis task. Within most critical infrastructures, the combination of private enterprise and government agencies is charged with standards and review of conformance. Less attention is paid to the issues surrounding horizontal integration, where a failure in one area can trigger secondary failures.

Political forces have great control over resource allocation. Failed systems attract the notice of policy makers and receive resources for rebuilding and repair. This draws material and effort away from systems that are working well, which in turn reduces their reliability. In the absence of concerted efforts to test and probe for weaknesses – monitoring for near-miss events and failures that were abated before they escalated – successful systems are expected to remain successful. Slow and gradual decay of safety margins can occur until failure. Preparation for the next crisis requires resources that cannot be allocated to some other activities, which can produce more evident benefits. The best result that can be obtained from good crisis preparation is that "nothing happens"; this is a poor result for a society that prefers to see visible signs of progress. Thus, crisis preparation tends to be a low priority activity as the memory of past crises fades.

Crisis escalation and response complexity

Once a crisis is triggered, the visibility of the situation increases the importance of social and political elements in decision-making and prioritization of response. Many different agents have to cooperate even though they have different interests and goals. Imagine that there is a power cut for several hours in a large city due to a fire in a substation. Skilled and specialized responders have to work together: employees from the power companies who should repair the damaged facilities or put in place new ones, fire-fighters who take care of the fire and answer calls for help, police (or even the army) who will be responsible for public order, authorities who will communicate to population the current status of the crisis and the forecasts, other affected critical infrastructures, such as hospitals, transportation nets, oil, food and water suppliers, police stations, etc.

This means that all of them have to collaborate and share information during the crisis period, but this is only possible if they have previously established and updated efficient communication protocols. Otherwise, the absence of these protocols will confuse and delay the assignment of responsibilities and lead to inefficient use of resources and incorrect information about the developing situation.

Additionally, if the crisis has a wide geographical scope, the diversity of agents can be exacerbated due to the intervention of local, regional, national and even multi-national decision makers, such as the EU. These agents have different goals and perspectives, which lead to frictions on crisis time, when decision need to be taken in a fast manner. Hence, the boundaries of the responsibilities of the different administrations can become more diffuse during crisis.

Moreover, political tensions can limit both the response and the analysis and learning during the post-crisis phase. In this case the political need for local short-term protection can cause the breakdown of previously agreed mitigation protocols. A recent European cross-border power failure resulted in post-crisis disputes surrounding national responsibility [3, 4]. The response to subsequent crises will be hampered by the loss of trust among parties.

One final nagging concern is the vulnerability of infrastructure during crisis and post-crises recovery. Katrina was only one of three major hurricanes in the same season. On one hand, responders were able to reapply lessons. On the other, resources and supplies were stretched, slowing the recovery effort. It is foreseeable that an infrastructure already in crisis or stressed by a natural event could become the target of a secondary intentional attack. The need to redirect and redistribute resources could greatly destabilize an already tense environment.

Approaches to Modeling National Crisis Dynamics

Our research agenda includes the development of models that examine the effects of multi-national power crises in the European Union. We have chosen system dynamics modeling, with its high level of aggregation, so that we may capture the broad issues of concern in crisis management across infrastructures and borders. Other approaches to modeling add proven value as well, though they answer different types of questions. Agent-based techniques have been employed to develop numerous interesting models of crisis management. These models typically employ characterizations of typical behaviors by a multitude of individual actors before, during, and after an event. The behaviors of these individual actors combine to create the evolving dynamics of the crisis through unusual demands on resources and constrained capacities. An exemplar of this type of model is TRANSIMS, developed by Los Alamos National Laboratories. This agent-based model, started as a transportation and urban planning tool, is now employed in policy modeling of epidemics, weather, and other disasters. One common criticism of agent-based models is the degree of fidelity required in the matching of the programmed behaviors of the actors and their real-world counterparts. A deep understanding of the range of actions, reactions and decision models for various actors (or simplification of the same) adds to confidence in the model results. In addition, agent models tend to be computationally intensive and therefore somewhat less amenable to developmental use over a large problem domain.

Event simulation models of power grid components are common, as they play important roles in control, monitoring and training. These engineering models, while designed for other purposes, may contribute to crisis management planning. They encapsulate and support the operating assumptions of the power infrastructure and the individual characteristics of each component. These models can be applied in crisis planning as well, representing the information flows, integration with human judgment and operator decision-making. These models may suffer from tight coupling to their particular component, making abstraction more difficult. They may also not be easily integrated into larger-scale models.

Social network models have emerged as important contributors to crisis planning and management. These models identify the linkages that exist or emerge between organizations, individuals, agencies, and key decision-makers. Before an event these models can illuminate relationships that in turn become crucial flows of information and material once a crisis occurs, or how the interrelationships can cascade over time. Both post-Katrina and post-9/11 planning demonstrate the importance of these types of relationships in the deployment of resources in crisis response. Relocated disaster victims develop links to their new communities and may resist further change, while a salient and re-established social network encourages victims to return to their original homes.

All of these approaches provide benefit to decision-makers. Systems modeling draws problem behaviors from the structure of the underlying components and their interactions over time. Agent models are very useful when considering a highly structured and focused problem domain. Social networks provide insight into crisis management and likely paths of information dissemination.

The SEMPOC research program

The Simulation Exercise for Managing Power Cut Crisis (SEMPOC) project is a multi-year endeavor tasked with identifying and analyzing the vulnerabilities in the European Union power production and distribution network. We aim to integrate the significant elements of the long-term lifecycle of a power cut crisis, including technical, economic, political and social aspects into a holistic model. This requires an understanding of crisis management, a short-term activity embedded in a much longer-term one. The policy choices and plans that occur years before and after each crisis affects the ability to respond to the sudden changes that occur in power cuts.

We have chosen an iterative and expert-driven approach to model development. There is a great deal of expertise in the component domains of our task, but little cross-cutting knowledge. This led the team to construct small causal loop models reflecting local power outage concerns with appropriate experts using Group Model Building (GMB) scripts and techniques [13-15]. After the workshop the project team created running models based on the information gathered by the experts, and conducted intensive review of the runs and conclusions via phone or in person with the experts in attendance.

For the movement to a national-level model, we added new members to our reference group to add expertise in public safety, health, and crisis communication and expanded the time horizon. Later this year we will again expand the reference group and use the crisis simulation to review the policy options for the pre-crisis activities and cross-national concerns of our charter.

Explication of a National Power Grid Crisis

The national-level power crisis model workshop took place in San Sebastian (Spain) in May 2009.

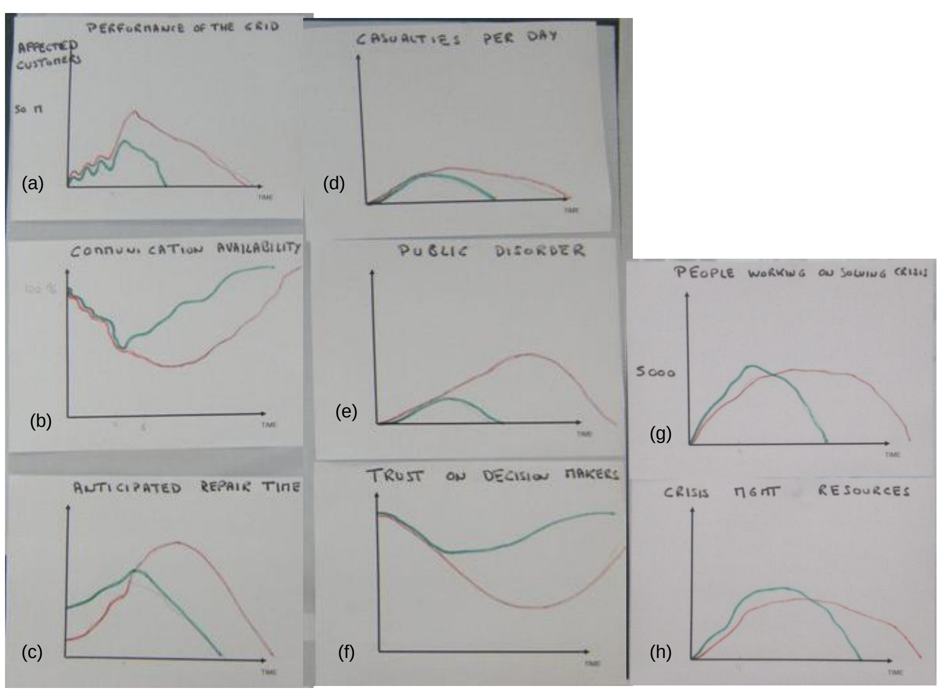

Figure 2: Sample behaviors of indicators (best case in green and worst case in red)

Eleven international / national emergency managers, power grid specialists and experts on supervisory control and data acquisition (SCADA) participated. During the two days of the workshop, exercises were conducted to identify relevant stakeholders (not shown), reference modes (Figure 2) and policy options (Figure 3). A draft causal model was created in the closing hours of the workshop.

The *Cnat* Model

After the workshop the modeling team distilled the various artifacts and commentary from the workshop into four sectors: Power Net, Clients, Government, and Sociopolitical effects (Figure 4).

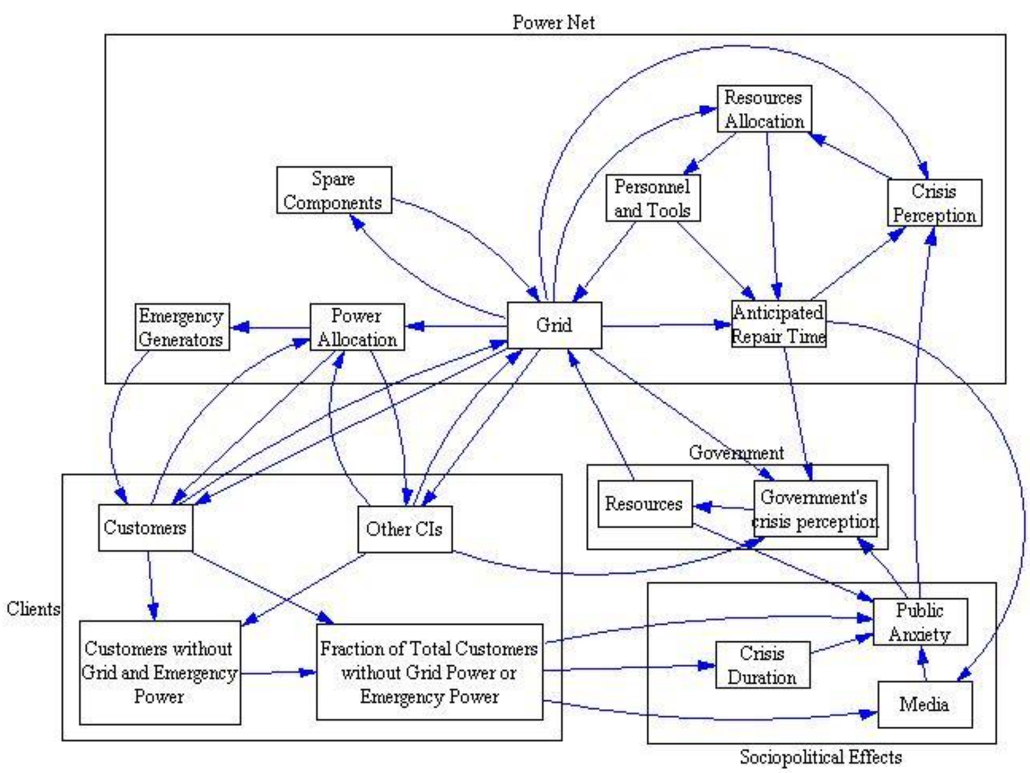

Figure 3 Expanded *Cnat* Model Sectors

Power Net

The Power Net sector captures the energy transfer technology and operations at the center of the problem domain. Electric power is an unusual commodity as it cannot be stored. Operators match demand and supply dynamically throughout the day. When a generation or transmission component goes offline or safe capacity is reached, operators reconfigure the grid to preserve service. Emergency generator capacity is often available for short periods, but an undersupply usually means obtaining power from other sources, subject to the capacity of the network, or shedding load. If the network is disrupted suddenly automated controls or operator actions open circuits to prevent further damage to the network, creating blackouts.

In a well-managed response, the damage to the physical network is minimal, and much of the grid may be restored by resetting circuits. When there is physical damage, the damage must be located, isolated, and repaired. A limited inventory of spare components parts are kept in inventory and deployed, through there is a delay associated with locating the specific points of failure, transporting the materials, and obtaining the skilled technicians required to perform safe installation. When an outage is widespread, such as those caused by severe winter weather, the logistics of repair can delay the restoration of service for many days.

A key influence on the dynamic behavior of this sector rests on the perception of the crisis on the part of power operators and managers. Their actions are based on information they have on the state of the grid, the suitability and effectiveness of repair efforts over time, and less tangible information about the state of public anxiety surrounding the crisis.

Clients

Our experts identified two distinct groups of power clients: Critical Infrastructure (CI) clients (e.g., hospitals, transportation) and other customers (e.g. businesses and consumers). One common pre-crisis preparation model includes identifying clients who agree to temporary supply reductions. In a crisis, power companies allocate power by an arranged priority scheme. CIs (and a small fraction of other customers) employ their own emergency generators, but these rely on the availability of fuel to run.

Customers without power, in both real and fractional terms, are important indicators of the effects of changes in the grid. These data condition the public and government's perceptions of the crisis, the media's reaction, the duration of the crisis and the public's behavior.

Sociopolitical effects

A power failure has immediate and direct economic and social effects. Besides the disruption of normal business and life activities, energy failures can trigger antisocial behaviors, such as looting and vandalism. Public safety personnel are hard-pressed to maintain order. All these factors generate tension in society, which is captured as public anxiety. Anxiety is influenced by the scope of the outage, its duration, and the information made available through media and government sources.

The media provides information and sets public expectations. If the time to repair and restore the power grid is longer than what the media expect and if the fraction of customers without power is greater than what the media expect, then the media's effect on the public will increase. This in turn influences government action as well as the operators of the power net.

Government

The government allocates resources to preserve public order, supplement the resources of repair crews, and help establish public calm. It relies on information from the power net sector and from the public to set its own expectations and adjust its efforts to manage the crisis. Careful application of governmental resources can reduce public anxiety, but this is dependent upon, among other things, the duration of the crisis. A poorly-managed government program can increase public anxiety and slow the rate of recovery.

Cnat Model Runs

The C*nat* model is calibrated to a two-week crisis and recovery. Our base run (Figure 5) assumes that a serious crisis has occurred at time 0, with 25% of the physical network damaged and requiring either repair or inspection. The dynamics of the crisis are captured through four variables:

- Power net status: the percentage of the power net that is working properly.
- Anticipated Repair and Restoration Time: the estimated time (in days) needed to repair the damaged components and restore the power net.
- Fraction of Total clients without grid or emergency power:
- Public anxiety: A subjective value [0 ,0.5] of the state of the public mind.

Our parameterization and dynamic results have been reviewed with expert panels through a series of structured interviews, discussed elsewhere.

Base Run

At day 0, when the outage occurs, the Power Net Status drops precipitously (line 1). The inspection and restoration process proceeds as expected, with most customers back online within a day. The remaining customers are brought back as repairs permit, returning to full capacity by day 12. Anticipated Repair and Restoration Time (line 2) rises quickly from one day to seven days as more information becomes

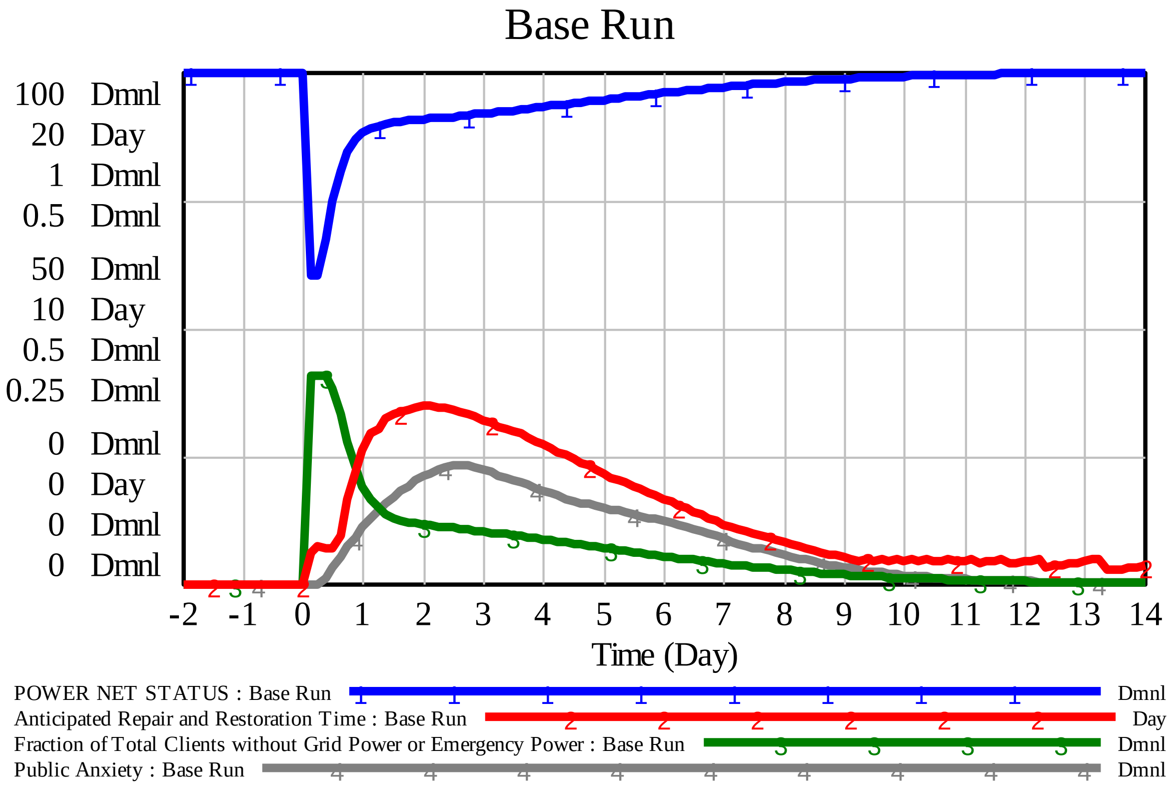

Figure 4: *Cnat* Base Run -

available about the extent of damage. By day 2, however, the anticipated time for complete restoration is estimated with more precision, and drops off as work progresses.

At the outset of the crisis, the fraction of clients without grid or emergency power spikes to about .4 . Within a day, half of the customers are back online, with the others coming back as the grid infrastructure is restored. Public anxiety about the crisis and its longer-term effects increases from the outset, first from considerations of immediate issues, and later through concerns about economic losses secondary to the outage. Once the repair effort seems on track, anxiety falls off.

Government has more resources

An increase in available government resources has a small effect on the overall crisis duration and effects

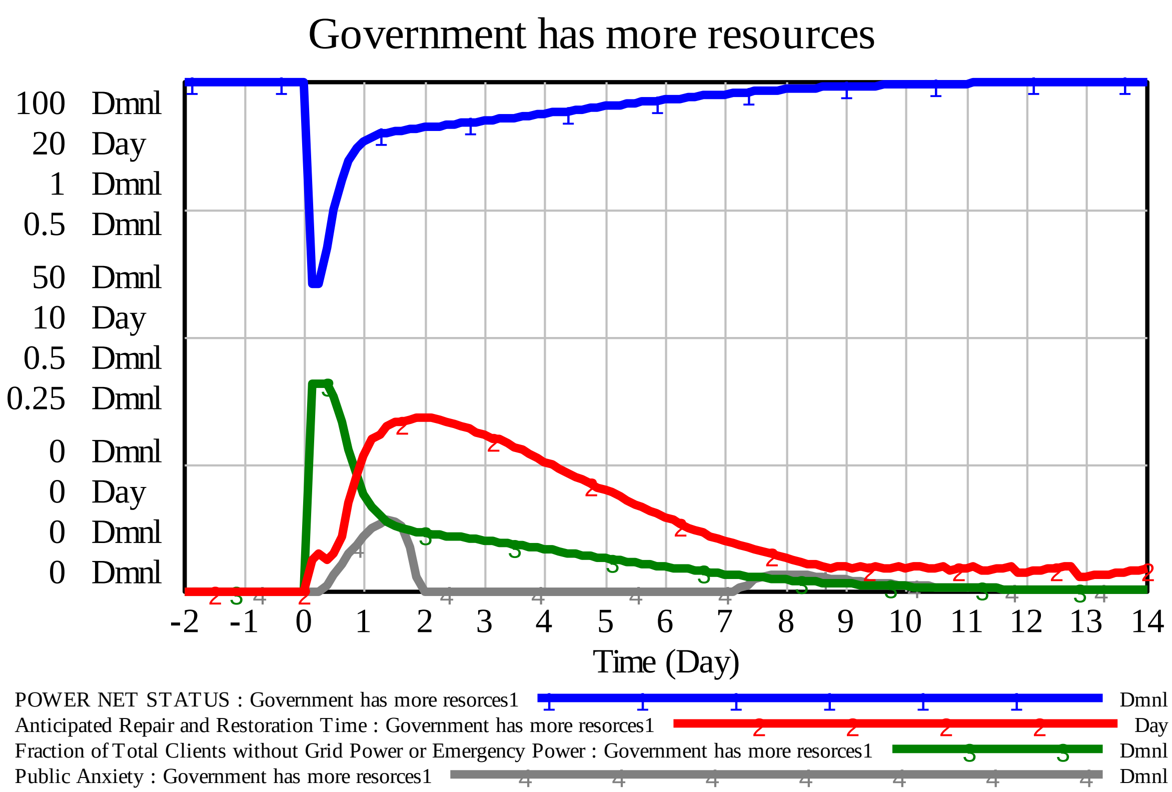

Figure 5: Government has more resources

(Figure 6). As government's role during the crisis is the maintenance of public order, public anxiety is reduced. The other aspects of the crisis are comparable to the base run: The power net is recovered by the day 12, anticipated repair time and customers without power have identical trajectories.

High Impact Event

A more damaging crisis, as one might expect, affects more customers and takes longer to restore. After two days the true extent of damage is understood, but public anxiety remains elevated. The longer-term implications of elevated anxiety will be an important policy driver when *Cnat* is integrated into a full life cycle model (Figure 7).

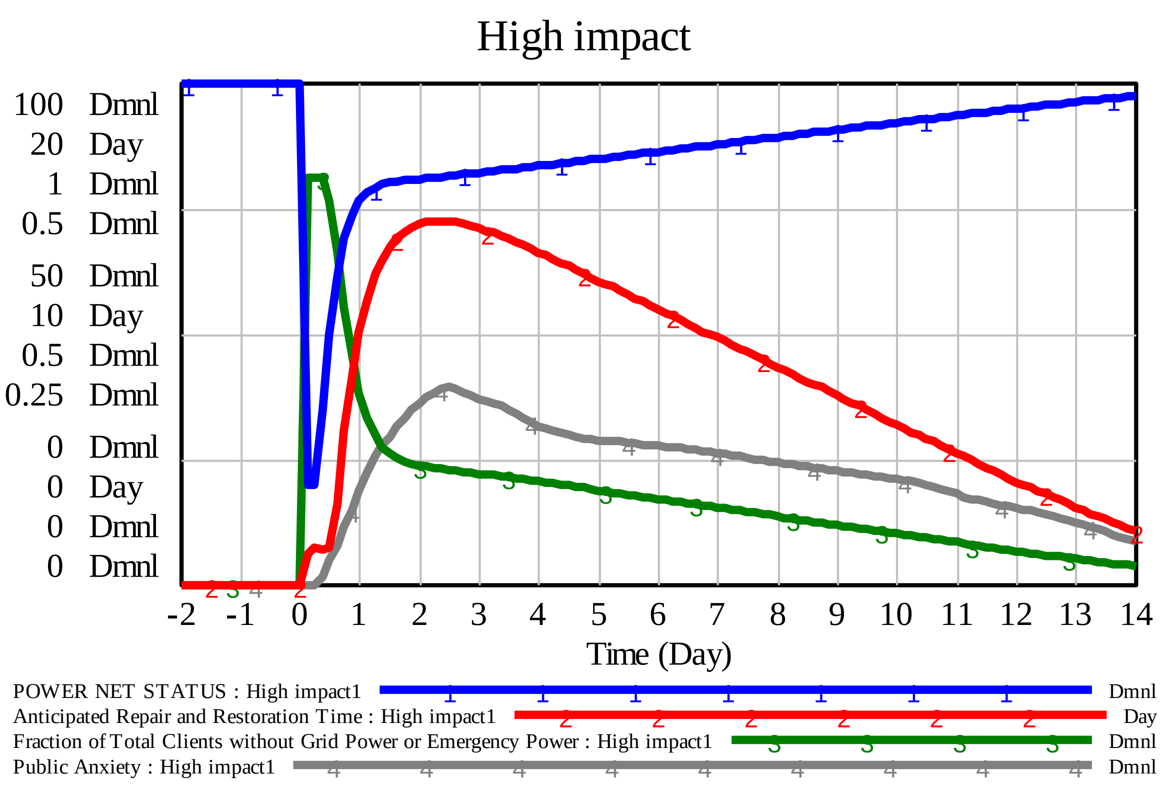

Figure 6: High Impact Crisis

Media effects

The media also play an important role in the behavior of public anxiety. In this simulation, the accuracy of the information provided by the media is reduced. While the true state of the power net is the same as in the base case, the inaccurate portrayal of the situation increases public anxiety. Again, the secondary effects of increased anxiety are likely to affect the post-crisis analysis (Figure 8).

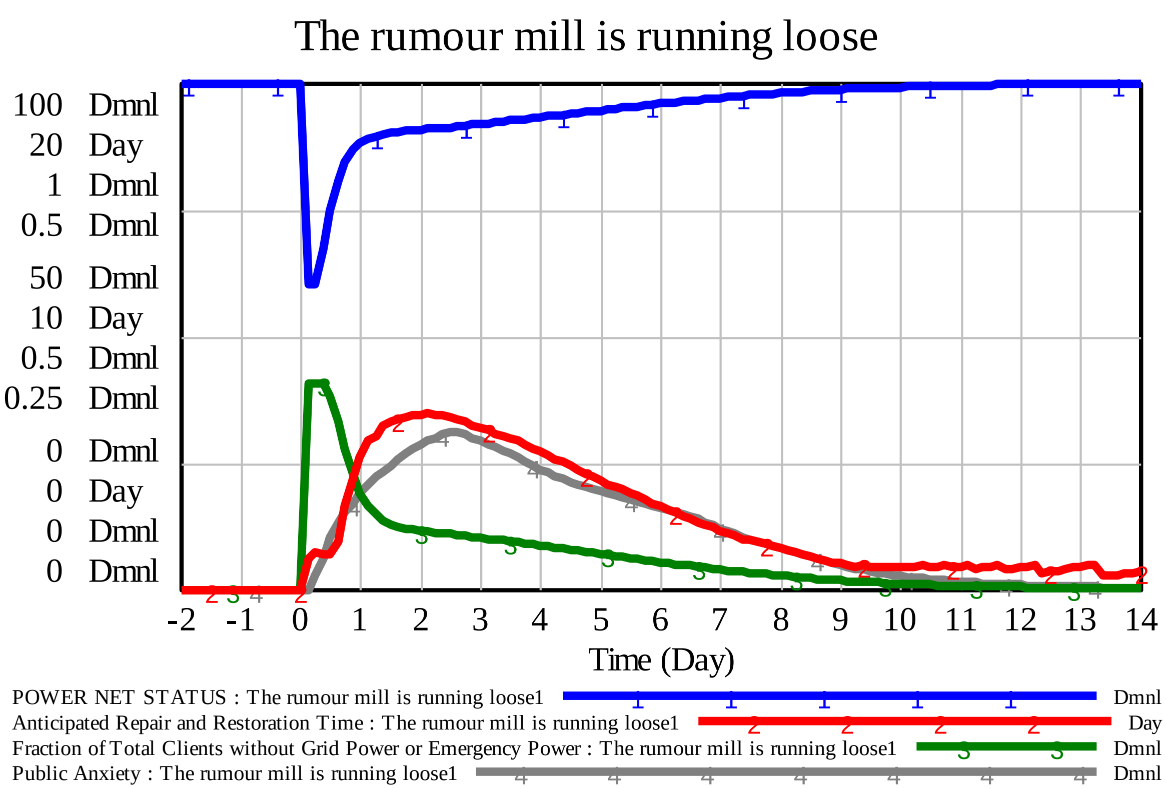

Figure 7: Media Effects

Longer duration impact

Some power outages cascade over time, where early failures may trigger subsequent ones. This run shows the same number of affected units as the base run, but the units fail over a period of days. The Power Net Status does not drop as severely as in the base case, as repair crews are not as strained and replacement parts can be replenished. The fraction of total clients without power is less than in the earlier cases. The longer duration does wear on the clients, and public anxiety is higher (Figure 9).

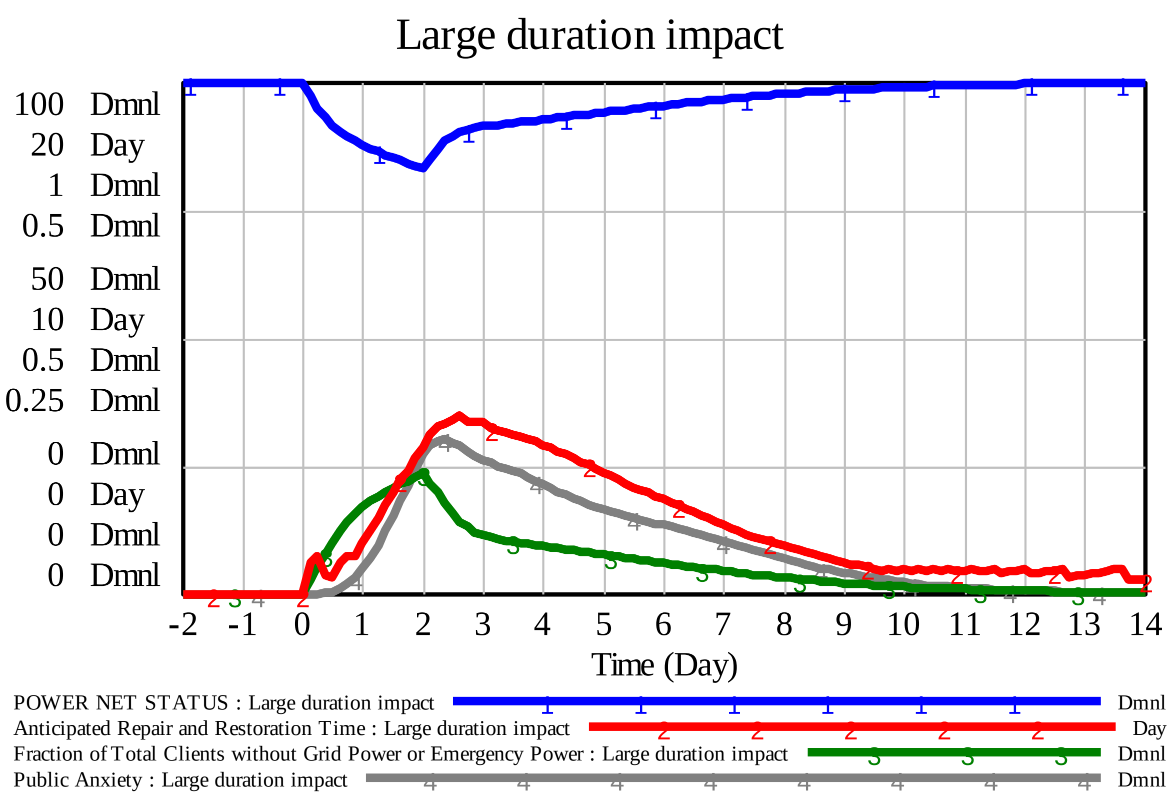

Figure 8: Longer Duration

Future research

The increasing interdependence of the EU power grid demands a new crisis management approach, one that anticipates the need for policy and procedures at a cross-national level. The SEMPOC project includes the development of simulation tools that explore the effects of large-scale events and the effect of policy choices on their ability to respond. The *Cnat* model is one element of this program, capturing the behaviors seen in past power crises.

The *Cnat* model is also a transitional work product. It represents the behavior of one type of crisis, a power outage, with a 14 day timeframe. The pre- and post-crisis activities that define the state of the system at the point of crisis take years to develop. Our work with crisis managers taught us that before we move to long-term policies, it is necessary to demonstrate the fidelity of a crisis model to their expectations. With this in place, our expert panel is confident in the transition to larger scale policy issues.

References

[1] "More Swedish Power Next Week (Mer svensk atomkraft til uken)," in *Verdens Gang* Oslo, Norway, 2010. Available at http://www.vg.no/nyheter/innenriks/artikkel.php?artid=579672.

[2] US-Canada Power System Outage Task Force, "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," US Department of Energy & Canada Ministry of Natural Resources 2004. Available at https://reports.energy.gov/BlackoutFinal-Web.pdf.

[3] Commission De Régulation de L'Énergie and Autorità per l'energia elettrica e il gas, "Report on the events of September 28th, 2003 culminating in the separation of the Italian power system from the other UCTE networks." Available at Co.

[4] Union for the Coordination of Transmission of Electricity (UCTE), "Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy," 2004. Available at http://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/20040427_UCTE_IC_Final_report.pdf.

[5] Union for the Coordination of Transmission of Electricity (UCTE), "Final Report: System Disturbance on 4 November 2006," 2007. Available at http://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/Final-Report-20070130.pdf.

[6] T. Birkland, *Lessons of Disaster: Policy change after catastrophic events*. Washington, DC: Georgetown University Press, 2006.

[7] S. L. Cutter, C. T. Emrich, J. T. Mitchell, B. J. Boruff, M. Gall, M. C. Schmidtlein, C. G. Burton, and G. Melton, "The Long Road Home: Race, Class, and Recovery from Hurricane Katrina," *Environment: Science and Policy for Sustainable Development* vol. 48, pp. 8 - 20, March 2006.

[8] W. T. Coombs, *Ongoing Crisis Communication: Planning, Managing and Responding*, 2nd ed. Los Angeles: Sage, 2007.

[9] C. Perrow, *Normal Accidents: Living with High-Risk Technologies*. Princeton, NJ: Princeton University Press, 1999.

[10] C. Perrow, *The Next Catastrophe*. Princeton, NJ: Princeton University Press, 2007.

[11] A. Stefanini and M. Masera, "The security of power systems and the role of information and communication technologies: lessons from the recent blackouts " *International Journal of Critical Infrastructures,* vol. 4, pp. 32-45, 2008.

[12] J. M. Torres, A. Alvarez, A. Laugé, and J. M. Sarriegi, "Russian-Ukrainian Gas Conflict Case Study," in *27th International System Dynamics Conference*, Albuquerque, NM, 2009. Available at http://www.systemdynamics.org/conferences/2009/proceed/papers/P1240.pdf.

[13] D. F. Andersen and G. P. Richardson, "Scripts for group model building," *System Dynamics Review,* vol. 13, pp. 107-129, Summer 1997.

[14] D. F. Andersen, G. P. Richardson, and J. A. M. Vennix, "Group model building: Adding more science to the craft," *System Dynamics Review,* vol. 13, pp. 187-201, 1997.

[15] G. P. Richardson and D. F. Andersen, "Teamwork in Group Model Building," *System Dynamics Review,* vol. 11, pp. 113-137, 1995.