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Sequencing Repairs after an Earthquake: An Economic Approach

Marco Casari

and

Simon J. Wilkie

California Institute of Technology
Pasadena, California

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Marco Casari

Departament d'Economia i d'Historia Econòmica
Universitat Autònoma de Barcelona
Barcelona, Spain

Simon J. Wilkie

Division of the Humanities and Social Sciences
California Institute of Technology
Pasadena, California

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University of California, Berkeley

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ABSTRACT

After recent earthquakes in the U.S. and Japan, the rebuilding of the gas, road, and electric power networks that constitute the lifelines infrastructure has shown that large welfare gains can be achieved by reshaping current emergency plans as incentive-compatible contracts with lifelines service providers. This report presents a class of mechanisms for repair works that a disinterested planner without comprehensive information about repair costs could adopt to implement in a preferred location and sequence. Such mechanisms would help to coordinate repair work among firms and set the correct location priorities. This approach may also be applied more generally to achieve efficient recoveries after other major natural disasters.

Keywords: earthquake reconstruction, public utilities, natural disasters, network externalities, mechanism design

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1 Introduction

Recently, many areas of public policy, from spectrum management to environmental policy, have benefited from the contributions of economists, particularly in the areas of game theory and mechanism design. In contrast, natural disaster reconstruction has been and still is largely managed by civil engineers. Although natural disaster prevention and assistance has long been regarded as a proper function of government, the professional economic literature on the topic is distressingly sparse (Hirshleifer, 1991). In this study we argue that current reconstruction procedures after floods, tornadoes, earthquakes, or even limited wars may greatly benefit from the adoption of mechanisms that are incentive compatible and that efficiently aggregate information.

Our close studies of recent postearthquake recoveries demonstrate once again that reconstruction after a major natural disaster is a complex task. In this paper we propose a mechanism to be adopted in emergency plans for the efficient recovery from a natural disaster. Because of their clear social importance, attention is focused on the restoration of those essential services known in the civil engineering literature as “lifelines”: water, electric power, and telephone systems. To the best of our knowledge, this is the first economic study of reconstruction procedures after earthquakes. The existing economic literature on earthquakes is devoted to risk coverage through insurance and through catastrophe bonds (Kleffner and Dherty, 1996; Penalva, 2003) and to policies that mitigate the damages of quakes (Kunreuther and Kleffner, 1993). Moreover, the present study differs from the operational research literature (Bryson et al., 2002) because we assume imbalance of information between the planner and lifelines firms.

Despite John Stuart Mill’s comment about the resiliency of human nature, “the great rapidity with which countries recover from a state of devastation; the disappearance, in a short time, of all traces of the mischiefs done by earthquakes, floods, hurricanes, and the ravages of war” (Mill, 1896), recent earthquakes in the U.S. and Japan have shown that rebuilding lifelines

is a challenging task that leaves considerable room for improvement (Chapter 2). After presenting the reconstruction problem (Chapter 3), we propose tools from the mechanism design literature to implement a socially optimal repair sequence (Chapter 4). Furthermore, a simpler, iterative procedure for the mechanism is presented (Chapter 5). The iterative mechanism can be safely employed when there are no network externalities, while in other cases the outcome might be suboptimal (Chapter 6). Chapter 7 presents conclusions.

2 Lessons from U.S. and Japanese Earthquakes

Recent experience in the rebuilding of lifelines such as gas, road, and electric power networks after the 1994 Northridge, California, and 1995 Kobe, Japan, earthquakes¹ has taught at least four important lessons (NERR, 1995; U.S. Department of Commerce, 1996; Schiff, 1998). First, the timing of lifelines repairs has a considerable impact on social welfare. Second, decentralized decisions by lifelines firms were not socially optimal. Third, economic incentives did change the behavior of lifelines firms, and otherwise could be employed to set different priorities and substantially speed in lifelines reconstruction. Fourth, at no extra cost the government could introduce a payment scheme that induces firms to incorporate into their decisions the full social costs and benefits of their repairs following a natural disaster.

Repair works after large-scale disasters take considerable time. Some individuals experience the early restoration of services, while others wait for days or even months, often at considerable cost. For example, fully restoring the Los Angeles water system to its pre-1994-earthquake conditions took more than two months and repairing the road network took six months. In the same earthquake, the major I-10 bridge in downtown Los Angeles had collapsed. For every extra day employed to rebuild the bridge, approximately 330,000 trips experienced long delays at an estimated social cost of \$1 million a day (NERR, 1995).

Moreover, field experience has shown clear instances of where decentralized coordination among lifelines firms failed. A postearthquake evaluation report of the reconstruction in Japan recommends that “hard, formal communication procedures should be established between gas, electric power, water supply, and fire department personnel.” (Schiff,

¹ The Northridge (Los Angeles) earthquake occurred on January 17, 1994 at 4:31 am PST and had a moment magnitude of 6.7. The epicenter was located 32 km west-northwest of Los Angeles, CA, US. The Hyogoken-Nanbu (Kobe) earthquake occurred on January 17, 1995 at 5:47 am JST in an area of complex faulting located near Awaji Island and the Hanshin area of Japan and had a moment magnitude of 6.9.

1998). One of the failures was the mismatch between the actions of the electric power and the gas companies:

One of the most important lessons associated with gas system performance during the Hanshin-Awaji [Kobe] earthquake is the need to coordinate the restoration of electric power with an assessment of the state of gas system repair.

It appears that there was no pre-arranged coordination between gas and electric company personnel to restore electric service in concert with shutting off and venting gas in areas severely damaged by the earthquake... [so] that early restoration of electric power in areas with leaking gas contributed to additional fires.”(Schiff, 1998).

After reviewing the evidence, Schiff (1998) advocates not just inviting lifelines firms to coordinate but establishing *hard, formal communication procedures* as integral parts of an emergency plan.

Besides the use of administrative directives, lifelines firms can also be induced through economic incentives as demonstrated by the reconstruction of freeway bridges after the Northridge earthquake.

For Interstate 10, the contractor agreed to complete work in 140 days [for an amount of \$23.8 million], with a \$200,000 daily bonus for early completion. Interstate 10 was reopened on April 11, 74 days ahead of schedule, which netted the contractors \$14.8 million in bonuses.”² (NERR, 1995).

As a result of this incentive scheme, the bridge was reopened in less than half of the agreed upon time, and the bonus amounted to 62% of the baseline compensation (\$14.8

² The estimates of the total cost of bridge replacements in a Caltrans report on Aug 16, 1994, were the following: On route I-10, La Cienega-Venice \$4 million, La Cienega-Washington \$34.6 million, Total \$38.6 million. A similar situation was true for the I-5 freeway: “Interstate 5 repairs were more difficult than those made on I-10; nevertheless, I-5 reopened on May 17, a month ahead of schedule, resulting in bonus payments of \$4.5 million for the contractor.” On route I-5, total costs were Gavin Canyon \$23.6 million, Butte Canyon \$6.8 million, total \$30.4 million (NERR, 1995).

million). Even so, the estimated savings to citizens from early completion of repair work was fivefold the sizable bonus paid to the contractor (NERR, 1995). Clearly, the lesson is that appropriately designed, incentive-based contracts can greatly affect repair works in a beneficial way for society.

Lifelines firms independently decided the pattern of repairs, but lifelines repairs after the Northridge earthquake were financed solely with federal and state funds.³ The approach advocated in this paper is that instead of giving public money unconditionally to pay for repairs, the government should introduce a payment scheme that promotes coordination among lifelines firms in such a way that induces them to incorporate into their decisions the full social costs and benefits. In the following chapters we construct a contract where a disinterested planner who does not know all the repair costs can nevertheless induce lifelines firms to implement the socially optimal repair sequence.

³ In the U.S., for any presidentially declared disaster, the related expenditures of all political jurisdictions and public utility providers qualify for a 75% federal refund, while 25% is funded by the state government. Owing to political reasons, in the case of the Northridge earthquake the federal government paid 90% and the State of California 10% (NERR, 1995. For a political economy analysis of federally declared disasters, see Garrett and Sobel (2002).

3 The Lifelines Repair Problem

We now present the essential elements of the lifelines repair problem after a major natural disaster. When lifelines firms independently choose the sequence of repairs, the outcome may be different than the sequence preferred by a disinterested and fully informed planner. A suboptimal outcome can originate either from a coordination failure among lifelines firms or from their setting repair priorities that maximize profits at the expense of society.

From the standpoint of a disinterested planner, decentralized, firm decision-making may nevertheless lead to a suboptimal repair sequence because of two types of externalities: the revenue synergy and the household surplus. The former externality originates from additional revenue generated when all the different lifelines firms coordinate repair work across locations. For example, suppose an earthquake damages the water and electricity networks of two hospitals, A and B, respectively, and the water firm first repairs Hospital A, while the power firm first repairs Hospital B. The result is that in the immediate postearthquake period, neither hospital can be opened. If instead both firms had first repaired the same hospital, one facility could be immediately operational in this critical period. The difference in firms' revenues between the coordinated but mismatched sequence is the "revenue synergy." In this example, as well as in the rest of the report, we make an "all-or-nothing" assumption regarding benefits flowing out of a location: a location generates revenues only when all the different lifelines in that location are repaired. As we shall see, whether firms coordinate can depend on how costly negotiations are.

"Household surplus," the second type of externality, provides a benefit to society greater than just increasing firms' revenues. This surplus originates both from consumer services being restored and the value gained by the reduction in health and public safety concerns. The analysis of an optimal repair policy must include both types of externalities because the household surplus does not need to be perfectly positively correlated with the revenue externality. For instance, consider the case where the public safety benefit is constant across households and

where poorer locations have a higher household density. When consumers' income positively affects expenditures in lifelines services, each location's total household surplus may be inversely related to its revenue for firms.

Because of the relevance of the household surplus, even when firms are able to coordinate on a sequence of repair work that fully exploits the revenue externality from synergies, there is still a role for a disinterested planner. So long as critical firms are owned by the local government the conflict between public and private interests is likely to be mitigated because the firm manager is accountable to the mayor or governor. The problem is likely to be more severe when lifelines firms are privately owned.

Some notation will be introduced to better illustrate the concepts just explained. The region affected by the earthquake can be described as a finite collection of locations, a_1, \dots, a_K . A location can be a physical sector, such as downtown, or a functional one, such as a set of hospitals. There are N lifelines firms. For simplicity we assume that one firm is in charge of one network in all the locations (either water, gas, or electricity). Moreover, we assume that in a single period, a firm can repair only one location. The elemental decision unit is to repair network j in location k at time t .

For a single firm, a sequence $s=(a_1, a_2, \dots, a_K)$ describes a way to repair the K locations and $s(k)$ denotes the location that will be repaired in period k , $s \in \mathbf{s}$.⁴ A sequence profile $\mathbf{S}=(s_1, s_2, \dots, s_N)$ describes an outcome for the collection of N firms, where s_j is the repair sequence for firm $j=1, \dots, N$ and \mathbf{S} is the feasible set, $\mathbf{S} \in \mathbf{S}$. A repair plan \mathbf{P} is an element of the feasible set \mathbf{S} . Moreover, the coordinated set $\mathbf{CS} \subset \mathbf{S}$ is the reduction of the strategy set, where all firms are required to choose the same sequence, $s_i=s_j \forall i, j \in N$. Formally $\mathbf{CS}=\{(s, s, \dots, s)\}$ but with a slight modification in notation we write $\mathbf{CS}=s$. Because of the "all-or-nothing" assumption, the optimal set \mathbf{S}^* is a subset of the coordinated set \mathbf{CS} .

The simplest illustration of the repair game can be done with two firms and two locations (Tables 3.1 and 3.2). Consider a situation where Firm 1 prefers to repair Location 1 first (sequence (1,2)), while Firm 2 prefers to repair Location 2 first (sequence (2,1)). That is the case when in Table 3.1 repair costs are $c_{12}=c_{11}=c_{21}=c_{22}=0$ and firms' ordinary one-period profits are $\pi_{12}=\pi_{21}=9$, $\pi_{11}=\pi_{22}=18$ (the first index is for the firm, the second for the location). The payoff sum is 0 when there is a mismatch and 27 when the firms coordinate. In this example, while the

⁴ This paper focuses on a sequence of locations and implicitly assumes that there is an optimal sequence of repair work within a location, the same in all locations, which is also specified and enforced by the emergency plan.

firms are indifferent as to which sequence they coordinate, as long as they do, when household surplus in Location 1 is higher than in Location 2, i.e., $h_1=14$ and $h_2=4$ in Table 3.2, the planner strictly prefers sequence (1,2) over (2,1).

Table 3.1 Firms' Repair Game

		Firm 2	
		(1,2)	(2,1)
Firm 1	(1,2)	$\pi_{11}-c_{11}-\delta c_{12}$ $\pi_{21}-c_{21}-\delta c_{22}$	$-(c_{11}+\delta c_{12})$ $-(c_{22}+\delta c_{21})$
	(2,1)	$-(c_{12}+\delta c_{11})$ $-(c_{21}+\delta c_{22})$	$\pi_{12}-c_{12}-\delta c_{11}$ $\pi_{22}-c_{22}-\delta c_{21}$

Notes: One-period profits, $\pi_{12}, \pi_{11}, \pi_{21}, \pi_{22}$ (first index is for firm, second index for the location). Repair costs, $c_{12}, c_{11}, c_{21}, c_{22}$; discount factor δ ; to obtain the gross payoffs, add $\delta(\pi_{12}+\pi_{11})$ to payoffs of Firm 1 and $\delta(\pi_{22}+\pi_{21})$ to payoffs of Firm 2.

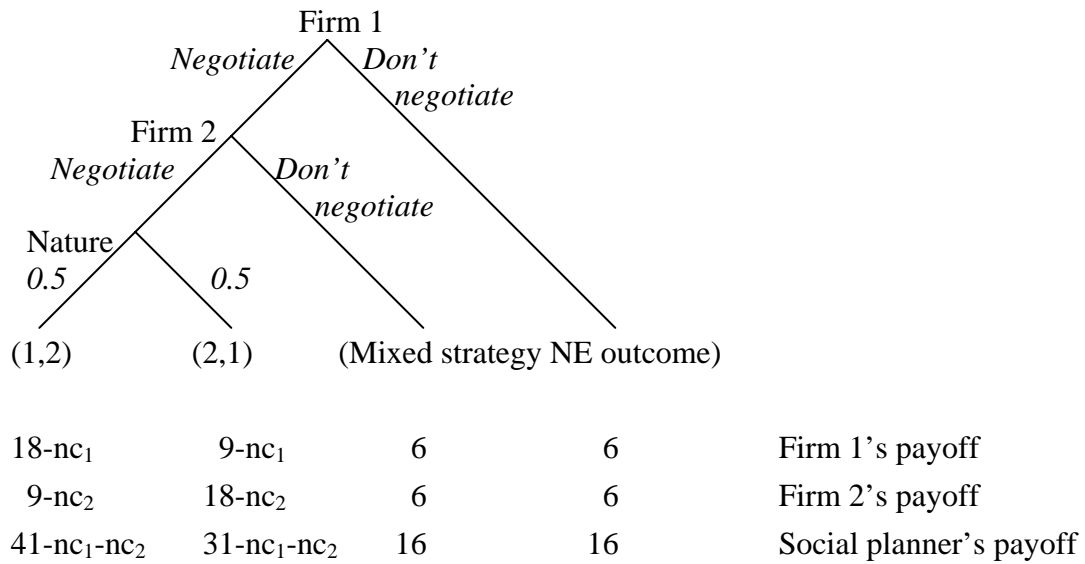
Table 3.2 Planner's Repair Payoffs

		Firm 2	
		(1,2)	(2,1)
Firm 1	(1,2)	$\pi_{11}-c_{11}-\delta c_{12}+\pi_{21}-c_{21}-$ $\delta c_{22}+h_1$	$-(c_{11}+\delta c_{12})-$ $(c_{22}+\delta c_{21})$
	(2,1)	$-(c_{12}+\delta c_{11})-$ $(c_{21}+\delta c_{22})$	$\pi_{12}-c_{12}-\delta c_{11}+\pi_{22}-c_{22}-$ $\delta c_{21}+h_2$

Notes: The planner's payoff is the sum of Firm 1 and Firm 2 payoffs plus household surpluses. h_k = household surplus from location k; to obtain the gross payoffs, add $\delta(h_1+h_2+\pi_{12}+\pi_{11}+\pi_{22}+\pi_{21})$; Feasible Set **S**: $\{(1,2),(1,2), ((1,2),(2,1)), ((2,1),(1,2)), ((2,1),(2,1))\}$; Coordinated Set **CS**: $\{((1,2),(1,2)), ((2,1),(2,1))\}$.

We now compare the outcomes both with and without the option to negotiate coordination by presenting three cases. In Case 1 there is no negotiation among the firms and we assume they will play the mixed strategy Nash equilibrium: Firm 1 chooses (1,2) with $p=2/3$ and (2,1) with $p=1/3$, while Firm 2 chooses (1,2) with $p=1/3$ and (2,1) with $p=2/3$. The corresponding outcome is a mismatch with probability $5/9$ and yields an expected aggregate payoff of 12. The difference between this equilibrium payoff and the maximum aggregate firm payoff defines the revenue externality, $27-12=15$.

The interaction between firms when they have an option to negotiate repair coordination can be illustrated by Figure 1. If both firms decide to negotiate, one common repair sequence is comparable to the flip of a coin. In Case 2 negotiation costs are zero, $nc=nc_1+nc_2=0$, and both firms will choose to negotiate because that results in an improvement on their individual mixed strategy payoff, from 6 to 13.5. The planner as well prefers this to the Case 1 outcome because $36>16$ (Table 3.2 or Figure 3.1). While firms cannot further improve their aggregate payoffs of 27, the planner could by always choosing sequence (1,2) and earning 41 instead of randomizing between (2,1) and (1,2) and earning 36. In other words, the private incentives of firms might lead to negotiate a coordinated sequence different than that desired by a disinterested planner.



Note: Without negotiation, the game is defined by Table 1 when $c_{12}=c_{11}=c_{21}=c_{22}=0$, $\pi_{12}=\pi_{21}=9$, $\pi_{11}=\pi_{22}=18$, $h_1=14$, and $h_2=4$. The mixed strategy Nash equilibrium outcome is a mismatch with $p=5/9$, sequence (2,1) with $p=2/9$ and sequence (1,2) with $p=2/9$.

Figure 3.1 Firms' repair game with the option to negotiate coordination

In Case 3 we introduce positive negotiation costs, $nc>0$. When such costs are exceedingly high, not even a disinterested planner desires that the firm engage in negotiation, $nc>20=36-16$. The trouble with decentralized negotiation though is that it does not happen often enough. When $15>nc>20$, it is never in the firms' best interests to enter negotiation, although it would increase the planner's payoffs. Moreover, because negotiation costs need to be paid before a firm knows what the agreement will be, an asymmetric negotiation cost structure may prevent a firm from entering negotiations. For example, with $nc_1=0$ and $nc_2=8$, Firm 1 wants to coordinate as it

expects a net improvement in payoffs of 7.5, but Firm 2 is not interested because $nc_2=8>7.5$. Without side transfers, no coordination takes place despite an aggregate expected net improvement for the firms of 7.⁵

Actual difficulties in coordination among firms in the field suggest that negotiation costs are actually substantial. Sources of such costs may be the time pressure that lifelines firms face in the period immediately following a major disaster, which makes negotiation highly costly. Moreover, a firm might be bound by rights contractually granted to some customers that entitle them with a priority over others in having the service restored. As breaching these agreements could be costly, a firm might then not follow the most efficient repair plan because of the initial allocation of property rights among customers. While negotiation costs may be sizable for firms and sometimes may impede coordination on a common repair sequence, the household surpluses that are generated after a major earthquake are much larger than negotiation costs and hence coordination generates a net social benefit.

Adding high penalties for failed coordination through an emergency plan is likely to bring the chosen repair sequence closer to the planner's most preferred repair sequence. Stimulating coordination through the emergency plan sponsored by the state or the city council could also reduce negotiation costs. In fact, it provides a framework for communication and it might make implicit side transfers easier to contract upon and to enforce. Moreover, it could override without compensation the allocation of the priority rights previously contracted by lifelines firms with individual customers.

⁵ When side transfers between firms are possible, in the absence of transaction costs there should be no inefficiency. An experimental study of the Coase theorem by McKelvey and Page (1997) finds support for this conclusion but also reports that inefficiencies still arise when negotiation costs are private information.

4 An Incentive-Compatible Mechanism

An emergency plan that includes appropriate economic incentives could help to direct the repair of earthquake damage to lifelines networks along an efficient path. This section describes a class of mechanisms that achieve efficiency when lifelines firms know repair costs but the planner does not. This informational imbalance marks the difference between the mechanism design approach and the operational research literature. A planner with comprehensive information about the costs and benefits of all possible repair plans can compute the best plan, command each firm to execute it, and transfer appropriate funds to cover the costs. In this study we assume that in the event of an earthquake, the information acquired by firms on the repair costs c_{jk} is private. Without that information the planner is unable to determine the optimal plan. The mechanism design literature has devised ways to give firms the incentives to truthfully reveal their best estimates of repair costs and then to implement the optimal repair sequence. This approach can generate large gains for society compared to the current procedure of simply letting firms freely decide on repair sequences and then paying them after completion of the work. Before considering those mechanisms, we list other assumptions about the repair problem. Some of these consider the technological environment (1–3), while others consider the behavior of the agents (4–5):

1. *All-or-nothing value.* At time t location k yields positive revenues for both firms and society only when *all* lifelines services have been restored, $I(t,k,S)=1$. More formally, the indicator function $I(t,k,S)=I\{\exists z_j \leq t \text{ such that } k=s_j(z_j) \text{ for all } j\}$ equals 1 when location k appears in the repair sequence s_j of each firm j at a time z_j earlier than or equal to time t , and equals 0 otherwise. The expression $s_j(z)$ denotes the z^{th} element in the location sequence s_j , where $S=(s_j, s_j)$.
2. *Positive household surplus.* Lifelines services generate consumer surplus and reduce health and public safety concerns, $h_k \geq 0 \forall k$.

3. *Repair technology.* This assumption is a list of simplifying conditions about repair technology. It makes the technical analysis of mechanisms easier.
- (a) A firm needs one “period” to repair the network in one location;
 - (b) A firm cannot repair two locations in parallel in the same period;
 - (c) Firms can work simultaneously in the same location (no congestion); and
 - (d) Repair costs for a given lifeline do not depend on the damage level of *other* lifelines in the *same* location.
4. *Firms are profit maximizers.* The present value of firm i 's profits has two components: a negative component that depends on the one-time repair costs c_{ik} , and a positive component that is linked to the ordinary one-period profits π_{ik} . Ordinary profits are cashed for the locations already repaired, i.e. $I(t,k,S)=1$. Notice that there is a positive discounting factor of time, $\delta < 1$. A firm $i=1, \dots, N$, $\text{Max}\{\Pi_i(S)\}$ over sequences $s_i \in \mathbf{s}$.

$$\Pi_i(S) = \sum_{k=1}^K \left(-\delta^{k-1} c_{i,s_i(k)} + \sum_{t=1}^K \delta^{t-1} I(t,k,S) \pi_{i,s_i(k)} \right) \quad (1)$$

5. *Planner's objective function.* The planner's objective function includes the discounted realized household surpluses $h(S) = \sum_{k=1}^K \sum_{t=1}^K \delta^{t-1} I(t,k,S) h(a_k)$ as well as the sum of the firms' profits Π_i (expression (1)). Notice that the discount factor is the same for firms and the planner. The planner $\text{Max}\{W(S)\}$ over sequences $S \in \mathbf{S}$.

$$W(S) = h(S) + \sum_{i=1}^N \Pi_i(S) \quad (2)$$

Assumption 5 states that the planner is disinterested because the planner considers firms' profits and repair costs, and household surpluses. It might be argued that politicians will adopt a different objective function, particularly in cases when a decision that explicitly assigns the lowest repair priority to their location would increase the chances of alienating voters. Two remarks can be made in defense of Assumption 5. First, the additional resources generated by a more efficient repair plan may better achieve other ends. It is hard to argue for objective functions that favorably evaluate miscoordination among lifelines firms. Second, re-election goals may require giving greater weight to household surpluses instead of the profit motives of firms.

The mechanism design literature models the interaction of individuals by game theory tools, whereas institutions governing interaction are modeled as mechanisms. In a mechanism each individual has a message (or strategy) space, and decisions result as a function of the messages chosen (Jackson, 2001). Our task is to find a mechanism for this context such that under the assumption that firms maximize profits, the outcome will be one that maximizes the planner's objective function instead.

A theme that comes out of the mechanism design literature is that it is often impossible to find mechanisms compatible with individual incentives that simultaneously result in efficient decisions (maximizing total welfare), the voluntary participation of the individuals, and balanced transfers (taxes and subsidies that always net out across individuals). Nevertheless, there are some important instances of when incentives and efficiency are compatible, whereas in others a "second-best" analysis is also possible (Jackson, 2001). The role of transfers is to give individuals an incentive to correctly report their private information so that the collective decision made is efficient. To get a truthful revelation of the private information, adjustments need to be made so that individuals are taxed or subsidized based on the announced valuations. In some mechanisms transfers do not sum up to zero across individuals in all states.

We now present the application of a mechanism, known as the "pivotal mechanism," to earthquake repair sequencing. This application results in the choice of an efficient sequence although some individuals may not voluntarily want to participate and as a result, the transfers may not be balanced. These issues will be discussed later.

Consider the N lifelines firms plus a special agent representing citizens. We assume that individuals' utility is quasi-linear, i.e., it includes a numeraire commodity, generally interpreted as money, such that preferences are separable and linear in this commodity. This assumption is satisfied in the earthquake context. More specifically, firms' utility is $u_i(S, y_i, \theta_i) = \Pi_i(S, \theta_i) + y_i$ for $i=1, \dots, N$, and the citizen-agent's utility is $u_{N+1}(S, y_{N+1}, \theta_{N+1}) = h(S, \theta_{N+1}) + y_{N+1}$. Let the choice space be $X = S \times Y$, where S is the set of possible repair sequences and $Y = \mathbf{R}^{N+1}$ are the transfers from the planner to each agent. The transfers might include an amount determined before running the mechanism in order to facilitate voluntary participation to the mechanism. An individual type $\theta_i \in \Theta$ is determined by the profile of one-period profits or surplus and repairs cost profile, $\Theta = \mathbf{R}^{2K}$. Repair costs for the citizen-agent are always set to zero. While the one-period profits and surplus are public information, the repair costs could be the private information of each firm.

As the mechanism designer we want to find a choice function:

$F: \Theta \rightarrow X$ that, given the cost structure, picks an outcome $x=(S^*, y_1, y_2, \dots, y_{N+1})$, where the sequence S^* is efficient after the fact, i.e.,

$$\forall S \in \mathbf{S}, h(S^*, \theta_{N+1}) + \sum_i \Pi_i (S^*, \theta_i) \geq h(S, \theta_{N+1}) + \sum_i \Pi_i (S, \theta_i).$$

According to the pivotal mechanism, which is a special case of a Groves mechanism, the following social choice function is efficient:

$$y^*_i = [h(S, \theta_{N+1}) + \sum_{j \neq i} \Pi_j (S^*(\theta), \theta_j)] + k_i (\theta_{-i}) \text{ for } i=1, \dots, N \text{ and } y^*_i = [\sum_j \Pi_j (S^*(\theta), \theta_j)] + k_i (\theta_{-i}) \text{ for } i=N+1,$$

where $\theta=(\theta_1, \dots, \theta_{N+1})$.

The function k_i is $k_i = -h(S^*_{-(N+1)} (\theta_{-(N+1)}), \theta_{N+1}) - [\sum_{j \neq i} \Pi_j (S^*_{-i} (\theta_{-i}), \theta_j)]$ for $i=1, \dots, N$ and $k_{N+1} = -[\sum_j \Pi_j (S^*_{-(N+1)} (\theta_{-(N+1)}), \theta_j)]$. The expression $S^*_{-i} (\theta_{-i})$ is the efficient sequence in the absence of agent i .⁶ This transfer y^*_i is always nonpositive and so the pivotal mechanism is always feasible, $\sum_i y^*_i \leq 0$ and has a nice interpretation. If i 's presence makes no difference in the maximizing choice, i.e., $S^*_{-i} (\theta_{-i}) = S^*(\theta)$, then $y^*_i = 0$. Otherwise, we can think of i as being “pivotal,” and then y_i represents the loss in value imposed on the other individuals due to the change in decision that results from i 's presence in society. The pivotal mechanism then has a very simple intuition behind its incentives: each individual's transfer function takes into account the marginal social impact (on other individuals) made by the individual's announcement of θ_i . When looking at this social impact, together with the individual's own selfish utility, the individual has exactly the total social value in mind when deciding on a strategy thereby leading to efficient decision-making (Jackson, 2001).

The Groves mechanism presents two attractive features for our application. First it truthfully implements the efficient outcome in dominant strategies. Second, it is rather parsimonious in terms of repair cost knowledge on the side of the firms. If the equilibrium strategy is dominant, a strategy is the best regardless of the strategies chosen by other individuals. A firm does not need to condition its strategy upon what information it thinks other firms will be providing to the planner as it must do when the solution concept is, for instance, the

⁶ In particular $S^*_{-(N+1)} (\theta_{-(N+1)})$ is the repair sequence the maximize firms' aggregate profits.

Nash equilibrium. In many respects, a dominant strategy equilibrium is more robust than a Nash equilibrium one. Moreover, a firm needs to know only its own repair costs and nothing about those of other firms, and the planner can be totally uninformed.

The two drawbacks, which have already been mentioned, concern the transfers not being balanced and the voluntary participation issue. The problem of unbalanced transfers is related to the status of the special agent representing citizens and acted upon by the planner herself. When household surpluses are “responsible” for changing the sequence preferred by the firms, the citizen-agent might have to pay a transfer, $y_{N+1}^* > 0$. Two cases are possible. In Case 1, neither the planner nor the citizens are paying the transfer but yet the socially preferred sequence resulting from the mechanism is implemented. In this case, the issue is whether the planner has correct incentives to truthfully set the level of household surpluses h_k . If so, transfers from firms could be assigned to the citizens as well. The planner could set h_k based on constituency interest or on bribes rather than the actual household surplus of the citizens. In Case 2, the planner does pay the transfer. In that case the pivotal mechanism becomes an instrument of discipline not only for the firms but also for the planner. The problem, then, is how to remove the transfers from the system as the mechanism requires. One solution would be to relegate them to the upper level of government.

The second issue is that it might not be in the lifelines firms’ best interests to either voluntarily sign the contract or to carry out their contractual obligations. The emergency plan must be prepared before the event of an earthquake and hence a firm must agree to use the mechanism before knowing the actual repair costs. At that stage the planner may promise a transfer to firm i to induce it to sign the contract. After the earthquake, the mechanism is run and the firm is legally bounded to fulfill the contract although it might imply negative profits. To satisfy the constraint imposed by voluntary participation after an event, the planner might need to promise a larger transfer beforehand or else afterwards risk pressure from the firms to renegotiate the contract.

Still, if a balanced budget is considered crucial, a class of mechanisms exists that accomplish this and implements the efficient sequence in the Nash equilibrium strategies or one of its refinements. When preferences are quasi-linear as in this context, one can apply, for instance, the mechanism proposed by Jackson, Palfrey and Srivastava (1994). We refer to the original article for the details but will give the flavor of the mechanism. The equilibrium strategy is to truthfully report a firm’s preferences in terms of all possible repair sequences and the same

information about another firm. The optimal sequence is implemented when, for all firms $i=1,\dots,N$, firm i 's announcement about firm $i+1$ coincides with firm $i+1$'s announcement about itself. Otherwise, an outcome undesired by the firms is implemented.

This other mechanism also has drawbacks. The major one is that it works when a firm knows not only its own costs but also the cost structure of at least one other firm. Hence, the pivotal mechanism is less demanding in this respect. Although several mechanisms could be compared, the conclusion is that tools exist to assist the planner in choosing the most efficient repair sequence.

5 An Iterative Decision Rule

A drawback of the mechanisms described in the previous chapter is the considerable information about repair costs that firms are assumed to know and report to the planner. This chapter illustrates possible directions for weakening these requirements.

Because of the high dimensionality of the strategy space for location sequencing, firms are required to submit a large number of cost estimates in order to implement the contract described above. As the mechanism stands, a firm i has to submit for each of the possible $K!$ sequences $s \in \mathbf{s}$ a cost vector $c_i(s) = (c_{i,s(1)}, c_{i,s(2)}, \dots, c_{i,s(K)})$, where $c_{i,s(k)}$ denotes the cost to repair location $s(k)$ given that locations $s(1), s(2), \dots, s(k-1)$ have already been repaired. The number of cost estimates that describe the full cost structure of a firm is $r = \sum_{j=1}^K \frac{K!}{(K-j)!}$. To give an idea of

this magnitude, if the region is divided into $K=10$ locations, $r=9,828,000$. Although most of the cost estimates reported will likely be repetitions of identical numbers, the amount of reporting required by the mechanism remains remarkably high. A dramatic reduction of the message space can be achieved without compromising the achievement of the optimal repair sequence when the following technological condition is satisfied in addition to the list in Chapter 4:

3(e) The cost of repairing the damage in a location a_k does not depend on the damage level of the *same* network in *other* locations a_l $l \neq k$.

When Assumption 3 (e) is met, a simpler, iterative version of the mechanism can be run. Instead of determining the whole sequence of locations in period zero, the iterative mechanism chooses just the next location to be repaired. After all lifelines are restored in one location, firms would again be asked to report repair costs on all the remaining locations, until all K have been repaired. In this simpler mechanism a firm i at period t submits its cost estimate $c_{i,s_i(t)}$ along with the cost estimate for another firm j , $c_{j,s_j(t)}$ given a common history of locations that have already been repaired, $s(1), s(2), \dots, s(t-1)$. When all K periods are considered, the number of cost

estimates to be reported relative to the cost structure of a firm is $r=(K+1)K/2$, considerably less than before (for $K=10$, $r=55$).

Besides reducing the strategy space, the iterative version of the mechanism has the advantage of allowing to incorporate into the decision-making process additional information on repair costs that might become available during the repair works. Committing to a repair sequence in period zero could result in a suboptimal choice if new information is acquired during the repair process.

6 Network Externalities

While the full-scale mechanism outlined in Chapter 4 always implements the optimal repair sequence, the iterative mechanism from the previous chapter may lead to the optimal sequence when there are network externalities. There is a network externality when the cost of repairing the damage in a location depends on the damage level of the *same* network in *other* locations. The impact of network externalities on the outcome of the iterative mechanism is now discussed.

Consider the scenario illustrated in Figure 6.1 where the water network consists of two aqueducts A and B (assume that other lifelines were not damaged). While Aqueduct B serves only Location 3, Aqueduct A serves Locations 1 and 2. In order to provide water to Location 1, the aqueduct must be repaired all the way upstream, i.e. also in Location 2. Hence, the current cost of restoring water supply in Location 1 varies whether Location 2 has already been repaired or not in previous periods. That is an instance of network externalities. We now compare the optimal repair sequence, $S^* \in \mathbf{S}$, with the repair outcome that results from the decentralized interaction of lifelines firms, $DS \in \mathbf{S}$, and with the outcome when employing the iterative mechanism described in the previous chapter, $MS \in \mathbf{S}$. In this example the adoption of the iterative mechanism leads to an outcome that is worse than having no mechanism at all.⁷

The iterative mechanism yields unsatisfactory results because it does not anticipate the consequences of today's repair decision on future repair costs. In fact, the repair cost reported by a firm has two distinct components, $c_{ik} = d_{ik} + e_{ik}$, the cost to repair lifeline i *within* location k , d_{ik} , and the cost for those lifeline i repairs *outside* location k , e_{ik} , that are nonetheless needed in order to provide service within location k .⁸ Whenever c_{ik} depends on past history of repairs, there is a network externality and Assumption 3(e) does not hold.

⁷ The example is biased on purpose against the mechanism, as it ignores coordination issues among firms— but is useful to make a point.

⁸ There is a third component, g_{ik} , which is the cost to repair the minor branches of the networks *within* location k . Without loss of generality we assume that $g_{ik}=0$. In the example, we also assume that $e_{i1}=d_{i2}$.

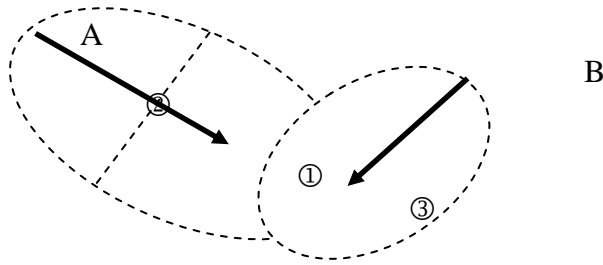


Fig. 6.1 A scenario with network externalities

Table 6.1 A scenario with network externalities

Location k	Repair cost within location k d_k	Repair cost outside location k e_k	Firm's ordinary one-period profits π_k	Household surplus h_k
1	3	$d_2 = 5$	4	3
2	5	0	5	1
3	1	0	3	2

Among the six possible repair sequences described in Table 6.1, the planner's optimal sequence is $S^*=(1, 2, 3)$. This outcome maximizes the sequence of net benefits, $(-1, 13, 17)$, which is the difference between the profile of benefits for all the locations that have already been repaired $(\pi_1+h_1, \pi_1+h_1+\pi_2+h_2, \pi_1+h_1+\pi_2+h_2+\pi_3+h_3)=(7, 13, 18)$ and the profile of costs $(d_1+d_2, 0, d_3)=(8, 0, 1)$.⁹

Instead, the iterative mechanism yields a sequence $MS=(3,2,1)$, which is not optimal. In the first period, when the reported cost vector $(c_1, c_2, c_3)=(8, 5, 1)$ is compared with the *three*-period benefits of each alternative $(3(\pi_1+h_1), 3(\pi_2+h_2), 3(\pi_3+h_3))=(21, 18, 15)$, Location 3 is chosen because it yields the highest *net* benefit (i.e., $15-1$). In the second period, with reported costs of $(8,5,\cdot)$ and benefits of $(2(\pi_1+h_1), 2(\pi_2+h_2), \cdot)=(14, 12, \cdot)$, Location 2 is chosen (net benefit

⁹ The sequence is optimal for discount factor $\delta > 0.67$. Repair costs are $c_1=8, c_2=0$ for sequence $(1,2,3)$ and $c_1=3, c_2=5$ for sequence $(3,2,1)$.

12-5). The resulting net benefit profile $(4, 6, 15) = (5, 11, 18) - (1, 5, 3)$ has a lower net present value than the profile for S^* .

Finally, a firm would have chosen $DS=(2,1,3)$ to get the highest net profit profile $(0, 6, 11)$. Although not optimal for the planner, the net benefit profile for $DS, (6, 13, 18) - (5, 3, 1) = (1, 10, 17)$ has a higher net present value than for the sequence MS generated by the iterative mechanism.¹⁰

A partial solution to network externalities is redistricting. So far we have been skeptical about the process of partitioning the region into locations, but such a task is an integral part of writing an emergency plan. The choice about the number of locations and their borders is not a trivial one and may influence the efficiency of the iterative mechanism outcome. In the above example, a consolidation of Locations 1 and 2 into a macro-location would eliminate network externalities. Once the iterative mechanism has selected a macro-location sequence, a lower-level mechanism could select micro-location sequences within each macro-location.

Still, restructuring the region into macro-locations is not completely satisfactory for three reasons. First, the planner must know how to properly redistrict the region into a location, which is a rather technical task.¹¹ Second, the larger the macro-location the smaller the potential surplus gains from applying the mechanism. Consider that a macro-location for a single lifeline such as electricity can be as large as — or larger than — the whole region under analysis. As an effect of the Northridge earthquake in Los Angeles, for example, 150,000 customers in rural Idaho lost power for three hours, as did power customers as far as Washington, Montana, and British Columbia (NERR, 1995, p.189). Third, when more than one lifelines network overlaps on the same map it may be impossible to divide the region in a way to eliminate all network externalities. To sum up, redrawing locations can solve the problem of network externalities in special cases but not in general, and hence the iterative mechanism can lead to suboptimal outcomes.

¹⁰ $(2,1,3)$ maximizes net profits for $\delta > 0.5$ and yields higher net benefits than $(3, 2, 1)$ for $\delta > 0.59$.

¹¹ In this work, the social planner is assumed not to be ignorant about the cost structure of firms.

7 Conclusions

Coping with natural disasters has long been regarded as essentially an engineering task (Bryson et al.; 2002, Hirshleifer, 1991). Despite this widespread belief, economists can also make a significant contribution in the design of reconstruction policies. In this report we have proposed that the introduction of economic techniques for the aggregation of information and the alignment of incentives in emergency plans for disasters can substantially improve social welfare.

Our focus is on postearthquake reconstruction and, in particular, restoring essential, or “lifelines” services such as water, power, and telephone services. A close consideration of the experiences of rebuilding lifelines networks after the 1990s earthquakes in the U.S. and Japan has made it apparent that current emergency plans are missing out on potentially large benefits to society (NERR, 1995; Schiff, 1998; U.S. Department of Commerce, 1996) by not having the proper mechanisms in place. Sources of inefficiencies lie in the dispersion of information among various key participants about the costs and benefits of alternative reconstruction plans and in a misalignment of economic incentives between the lifelines repair firms and society. We show how mechanism design theory can assist policy makers in acquiring the information to identify the best repair plan and in writing incentive-compatible contracts to implement that plan. The proposed approach can also be applied more generally to the recovery after other major natural disasters such as floods, tornadoes, and even to limited wars.

Although governments have paid the bills for lifelines repair works after an earthquake, they have permitted lifelines firms to decide what locations to repair and when to do it. Such decentralized decision-making is likely to generate inefficient outcomes because of coordination failures among lifelines firms and because of wrong repair priorities. Coordination failures arise when lifelines firms choose different sequences to repair locations. For example, if the gas firm repairs the west side of town while the power firm restores electricity in the east side of town, all

buildings are unusable because the west side lacks electricity and the east side has a fire hazard generated by gas leaks. Although in principle side transfers among firms should be enough to generate coordination, reconstruction reports indicate that coordination did not always occur (NERR, 1995; Schiff, 1998). Furthermore, wrong repair priorities can be set by firms when their profits are not strongly correlated with the consumer surplus resulting from services being restored and with the value gained by the reduction in health and public safety concerns. By contrast, a disinterested planner in such situations would choose a repair plan that would not have as its primary objective the maximizing of firms' profits.

We show that an emergency plan could avoid both coordination failures and the setting of wrong priorities by including a properly designed contract with lifelines firms. This type of contract has been studied in the mechanism design literature (Jackson, 2001; Jackson, Palfrey, and Srivastava, 1994). In general, firms are asked to reveal their private information about repair costs, and a decision about a sequence of locations to be repaired is generated by aggregating all the information. Transfers could be done from or to the firms. The role of transfers is to give firms an incentive to report correctly their private information. We present a class of mechanisms that achieves this goal and we apply it in the context of the pivotal mechanism, a classic example of an incentive-compatible mechanism where truthful information is the equilibrium strategy for the firms. The pivotal mechanism, however, does not ensure that the "budget always balances." That is, the sum of the payments by firms does not necessarily equal the sum of claims for payment by stakeholders. This, we believe, leads to a natural role for the federal government or, as a last resort, another disaster relief provider. For example, an agency like FEMA could have the role of disbursing funds to resolve such shortfalls after an earthquake.

Although current emergency plans would greatly benefit from incorporating the principles of mechanism design, it must be conceded that firms are required to report to the planner a remarkably high amount of information. In response to this criticism, we put forward an iterative version of the full-scale mechanism whereby firms are able to report repair cost estimates for a considerably lower number of alternative scenarios. Unfortunately, this simpler mechanism guarantees an optimal outcome only under restrictive conditions placed on the cost structure. Future research should explore trade-offs between the reduction in the amount of information to be reported and loss in terms of a second-best outcome.

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