Economic Model to Optimize Underground Utility Protection

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Abstract: The need for better protecting our vital infrastructure from being damaged or destroyed has received increased attention since the terrorist attacks on September 11, 2001. The tragedy of having thousands of innocent people die before the eyes of an entire nation awakened people to the reality of ''managed'' attacks of unthinkable magnitudes. However, tragedies of a smaller scale are a daily occurrence but accepted as ''collateral damage'' of work in an unsafe environment. This paper presents a cost-benefit analysis to address the question of how much money should be spent in protecting underground utilities from damage. During the study of an actual incident it was found that the total costs of such accidents are vastly underreported because only costs for emergency responses and repair are tallied up. This paper makes the case that a comprehensive approach for assessing the total economic impact of such incidents on the public, business, and government is the critical stepping stone to a mathematical optimization of expenditure for damage prevention. In addition, the reader will quickly realize that the use of the presented optimization model provides theoretical underpinning for the engineering profession in its effort to better protect our critical infrastructure from terrorist attacks.

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Introduction and Background

The congressional Transportation Equity Act for the 21st Century, TEA 21, Title VII, Subtitle C, SEC. 87301, states that: '' . . . unintentional damage to underground facilities during excavation is a significant cause of disruptions in telecommunications, water supply, electric power, and other vital public services, such as hospital and air traffic control operations, and is a leading cause of natural gas and hazardous liquid pipeline accidents.'' One does not have to look far to discover that Congress' findings are very well documented. Underground Focus Magazine (1999) is one such source that publishes an *Accident File* in every issue. For example, it listed seven major accidents that occurred between December 8 and 11 1998. On December 9, a fiber optic cable that supported the 911 service for five counties in Jacksonville, Tex. was cut by an excavation contractor. The most tragic accident, however, occurred on December 11 when ''a crew using an ''anchor cranker'' to install a guy wire anchor for a telecommunications pole augured into a gas main.'' Four people were killed and 14 injured when the gas exploded in St. Cloud, Minn.

Excavation accidents can occur as a result of mislocated or unlocated underground utility lines. Additionally, excavation or drilling/boring equipment, such as backhoes and directional boring rigs, cannot be controlled very accurately. Underground trenches are very crowded with utilities that are buried at various depths and following various courses. This makes it very difficult for an equipment operator to dig in an area without disrupting any of the utilities.

As stated in the document from Congress, these accidents cause problems for more than just the contractor and the utility owner; they are a great cost to society as a whole. Citizens, unrelated to the project, are inconvenienced and possibly injured or killed by the disasters.

Common Prevention Practices

There are many different parties, both actively and passively, involved in the excavation and trenching process. Active participants include: (1) owners of a new facility, (2) designers, (3) planners, (4) contractors, (5) utilities, (6) locators, (7) construction workers, and (8) equipment operators. In most any state of the U.S. a contractor is required by law to call a ''One-Call Center'' 48 or more hours before digging. In 1978, Connecticut was one of the first states to pass a ''Call Before You Dig Law'' the result of which reduced accidental cuts of utility lines by 60% while the length of new underground utilities being buried increased. Other states observed similar results after they implemented centers that ''receive notification of proposed excavations, identify possible conflicts with nearby facilities, process the information, and notify affected facility owners/operators.'' (U.S. Dept. of Transportation 1999) These utilities must have their lines located and marked using color that identifies their identity. According to the Uniform Color Code, red is used for electric lines, yellow for gas and oil, orange for communications, and blue for water. After the lines are marked on the surface, the construction crew may begin their digging operation, but have specific restrictions about how far away from the line they may dig. Unfortunately, this does not guarantee that all utilities remain undamaged. Tree roots that entangle cables, imprecise locating equipment, and loops that are hard to detect are just a few reasons why we still experience accidents today. Directional boring is not a panacea either. Spectacular accidents are constantly being reported (Underground Focus Magazine 1999) where a boring device damages

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Fig. 1. Computer aided design-integrated locating of existing buried utilities

a gas line or reams through phone cables. Furthermore, current utility detection devices are not capable of providing precise information about the depth of a detected line.

Fig. 1 presents a method for integrating traditional locating using a common sensor technology with the laser based spatial positioning system, Odyssey, that was tested by the Construction Automation & Robotics Laboratory at North Carolina State Univ. This integrated system would allow the automatic representation of a line, after it is detected, to be imported and overlaid onto an existing site map. Subsequently, this map could be fed to an excavator equipped with a similar spatial positioning system (Huang and Bernold 1997).

While One-Call Systems are the cornerstone for preventing utility damages today, other methods are being successfully tested, as well. One such approach has been given the name subsurface utility engineering (SUE), which basically represents a proactive problem solving method to damage prevention. Its core messages are: (1) let's establish an exact spatial map of all underground utilities, (2) use that map to route new utilities, and (3) update the maps with the new as-builts as we go.

Optimizing Protection

How much should we spend on SUE, detection, and prevention? In order to address this question appropriately, one must first become aware the actual cost of utility damages. Thus, the first question stated above leads directly to the second; What do damages to utilities cost? When searching the literature, one quickly realizes that the study of the economic impact of such accidents on private citizens, businesses, and government has not received much attention. In fact, the literature contains only a few studies about the cost of having a utility interrupted, primarily focused on the electric utility industry which is most interested in knowing the cost of ''brownouts'' from system overload. Without the knowledge of the true costs, it seems futile to calculate how much we should spend on utility protection efforts, be it before, during, or after a new utility is being placed underground.

Based on the need for cost data, this paper first presents an effort to analyze the cost of an accidental backhoe damage of a gas main, which resulted in an evacuation of residents and businesses. The results show that the economic impact of such accidents seems to be significantly higher than the direct costs that are commonly reported today. Subsequently, the paper will present a model for optimizing the investments for protecting underground utilities and end with a discussion of several concepts for assessing the true cost of potential accidents.

Table 1. Breakdown of Direct Costs of Natural Gas Line Rupture in 1996

Cost items	Amounts ($)
Fire department	7,477
Police department	3,759
Dept. of public works and utilities	4,532
Rescue team	1,025
Repair by gas company	20,000[a]
Total direct cost: (subtotal 1)	**36,793**[a]

[a]Estimate that does not include cost of the lost natural gas.

Costing Economic Impact of Gas-Pipe Damage

In 1996, during the construction of a new bookstore in a local community, a backhoe punctured a 1 ft (33 cm) diameter buried gas pipe. This incident was studied in a preliminary attempt to quantify the cost of a utility damage. The gas under high pressure shot 200 ft (66 m) into the air until a main valve was closed. Fortunately, the gas did not ignite. Nevertheless, the gas spread quickly into the surrounding neighborhood forcing the evacuation of all residents. One of the properties that was within the evacuation zone was a major shopping mall with 120 businesses. Our study covered the following parties: (1) municipal services, including the fire and police departments, department of public works, and emergency medical services; (2) the utility company that owns the severed line; (3) the stores and businesses that were evacuated; and (4) the residents that were evacuated from the surrounding areas. The municipal services mentioned, willingly participated in the survey. The utility company, however, was more cautious in releasing information because of continuing litigation. Seventy-two stores, approximately 60% of all mall stores, chose to participate in the survey. Of the one hundred twenty-two residents surveyed, forty returned complete surveys and 14 were returned, unopened and labeled ''return to sender.''

The main portion of the data collected in this case study was in the form of monetary losses incurred by the municipality and the utility owner. These losses are displayed in Table 1. Unfortunately, the study did not allow the compilation of the exact costs, such as the value of escaped gas, since it was not released by the gas company nor does it include the losses incurred by the general- and subcontractors working on the job, since the investigation was made long after the project was completed.

Some of the data collected from the businesses was in the form of direct monetary losses. The impact of the accident on the businesses and employees in the mall are displayed in Table 2. As

Table 2. Monetary Penalty of Evacuation to Stores

Cost items	Amounts ($)	Distribution (%)
Estimated total loss of sales for the 6 h evacuation	262,810	84
Estimated total wages lost to hourly employees	13,370	4
Total direct cost: (subtotal 1)	36,793	12
Total economic impact	**312,973**	**100**

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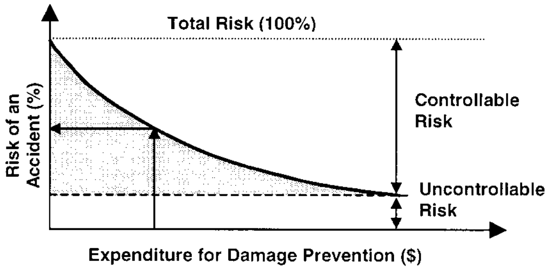

Fig. 2. Correlation between prevention efforts and risks of accidents

shown, the economic impact of the incident is assessed at $ 312,973 of which 88% can be considered consequential cost, since they are not directly related to the accident itself. In other words, the considered consequential costs are considerably higher than the direct cost. It is quite apparent that the presented consequential cost data should be considered as partial since much economic information was, and still is, inaccessible. Examples of additional costs include: (1) loss of income/sales taxes, (2) lost sales for gas company (gas main had to be shut down during repair), (3) losses to other utilities that could not sell their services during the time of evacuation (e.g., power), and (4) cost to shoppers who traveled to the mall only to be turned back by police. Last, but not least, the significant legal costs that ensue each time such an accident happens should be added, as well.

Since it is common practice to consider the $36,793 direct cost as the total cost of this particular accident, economically based decisions about the dollar amount to spend on prevention will be way off the mark. The question that presents itself is only how much should be spent? The following section will address this question by presenting an economic model based on marginal benefits for investing in prevention for the sole purpose of mitigating accidents.

Optimizing Expenditures for Damage Prevention

Optimizing damage prevention can be compared to optimizing car maintenance. It is common knowledge that money spent on oil changes and antifreeze will significantly reduce the risk of destroying the engine while on a trip, thus saving money and lots of aggravation. Still, the question about how often the oil should be changed does not lead to a simple answer. On a larger scale, such as maintaining vital utility lines, it seems economically prudent to define what the optimal amount should be.

Risk and Risk Avoidance

Utility companies can take actions which greatly decrease the likelihood of outages to their customers. Common measures include: (1) burying all utilities in a common trench (2) laying the utility deeper underground, (3) running backup lines to each customer, (4) encasing the utility in a non-destructible material, and (5) installing an early warning system. However, the extra cost of taking such actions must be compared with the benefit of the increased service reliability.

Fig. 2 depicts the relationship between the risk of damage and expenditures for its prevention. The nonlinear curve indicates that prevention dollars generally reduce the risk, thus called the controllable risk. However, no matter how much one spends, a small amount of uncontrollable risk, will always remain. In practice, this means that a perfectly reliable service is almost impossible to achieve, and then, only with large investments. The question that presents itself again is how much should be expended on mitigating the risk?

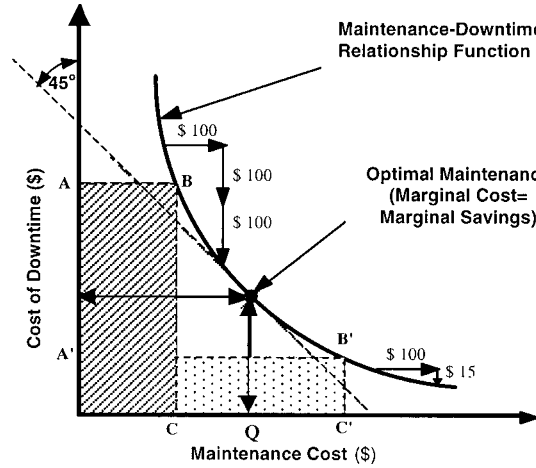

Fig. 3.

Optimization of Maintenance Using Marginal Costs

A common decision faced by production systems is how much to spend on maintenance in order to avoid a forced shutdown during operation due to a broken part. The real question is, how does the cost of a shutdown compare with the expenditures necessary to avoid it? As long as shutdown costs are much smaller then the avoidance cost, the rational decision is not to spend anything on maintenance. In a reversed case in which shutdown costs are higher, the production system should increase expenditure for maintenance until an additional shutdown loss equals the additional investment in order to avoid it. Fig. 3 illustrates graphically this method of optimization that is based on marginal savings.

The keystone to this method of optimization is the availability of a function that relates the expenditures for maintenance to the cost of total downtime. Fig. 3 shows this function in the form of a convex curve labeled maintenance–downtime relationship function. The goal of optimizing maintenance is to achieve minimal total cost, which is the sum of all downtime (C–B) plus the cost for all maintenance (A–B). As shown, case A–B–C expends very little on maintenance but incurs a lot of damages while case A′–B′–C′ spends a lot on maintenance which results in few damages.

The strength of this optimization model, however, is not the computation of absolute values. It is rather based on the ratio between an additional investment and the resulting cost reduction, graphically indicated by a tangent to the relationship function. As shown in Fig. 3, a $100 increase in maintenance would reduce the downtime cost by $200 when the starting point is in the proximity of B, but only a mere $15 around B′. In this range of the curve a $100 increase in prevention results in only $15 in savings. The optimal point on the relationship function curve is defined by the 45° tangent that represents the line where $100 in additional investment, referred to a marginal cost, will result in exactly $100 savings, referred to as marginal saving.

Marginal Optimization of Utility Protection

It is easily recognizable that the maintenance of a production system can be equated with the efforts to protect underground

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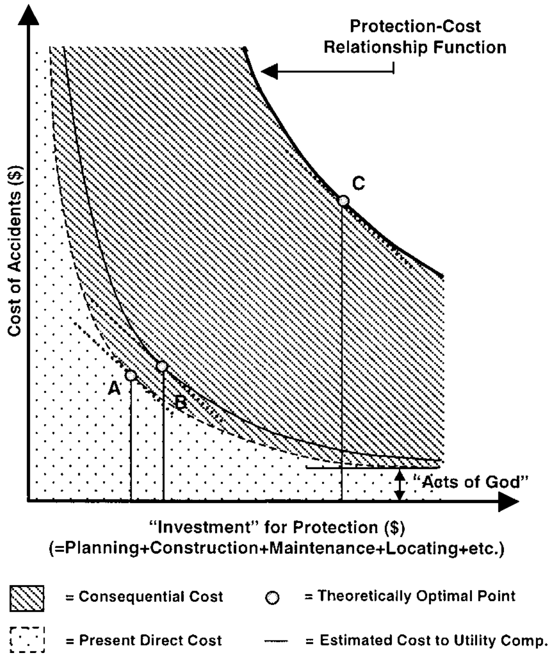

Fig. 4. Optimal damage prevention for various cost accounting schemes

utilities. Efficient maintenance includes the design of an easily maintainable system, damage-free installation, error-free calibration, startup, etc. This all costs money, but is usually well spent, since it is all done before linking it to the general system. Fig. 4 depicts how the marginal optimization concept can be applied to utility protection.

Three different cost estimates resulting from damages are plotted, leading to three different theoretically optimal investments of prevention A, B, and C. As can be observed from the graph, by adding the consequential costs to the direct cost of accidents, the optimum translates from A to C, indicating that more should be spent on protection.

The plots in Fig. 4 help answer the initial question about how much should be spent. It shows that the answer clearly depends on which cost function one uses. If only the direct costs are considered, the optimal is A. Consequently, if the total economic impact is considered, C becomes the optimum.

As stated earlier, marginal cost optimization depends on the existence of a reliable and complete investment–cost relationship function. As one intends to optimize utility protection efforts using total cost, similar to a business, one realizes immediately the lack of necessary cost data to establish the relationship function that leads to the definition of the theoretical optimum. A survey of the literature reveals, however, that several models have been proposed and tested that could provide a basis for establishing more or less meaningful relationship functions. The following section presents several of those methods primarily used to assess the economic impact of utility outages.

Value/Cost of Utility Outages to Its Consumers

The review of the literature disclosed that the electrical industry has developed models for the analysis of outage cost to consumers. Its incentive was the optimization of service reliability based on the risk function discussed earlier. It was determined that,

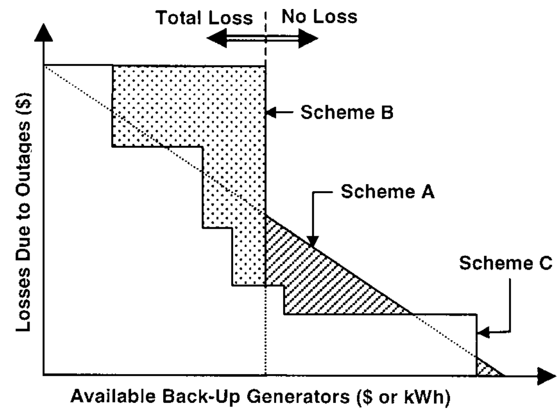

Fig. 5. Outage cost distribution for variable backup capacities (Beenstock 1991)

although there are some differences in the costs associated with utility outages other than electricity, the methods could provide a useful basis. The following sections briefly present the three main models used: (1) proxy, (2) survey, and (3) consumer surplus.

Outage Costs Based on Proxies

In general, proxy methods will only provide upper or lower bounds on the costs of an outage. As discussed in Caves et al. (1990), there are several proxies which are typically used by researchers. The first is the cost of back-up generators, used by Bental and Ravid (1982) and Beenstock (1991). Bental and Ravid assume that industrial plants act rationally, and would like to insure themselves, at least partially, against damages caused by power outages. Since generator installation and operation is costly, firms wish to choose the optimal amount of backup generating power so that their profits will be maximized. A competitive risk-neutral firm would, therefore, equate the expected cost of generating power on its own to the marginal benefit due to that power generation. The benefit includes all of the costs of outages which are avoided due to the backup power source. Since the expected marginal benefit from self-generated power is equal to the expected marginal cost of unserved electricity, the marginal cost of self-generation provides an estimate of the marginal outage cost.

Beenstock (1991) equates investment in generators to the purchase of insurance against the costly effects of stochastic power outages. A model is developed which is an extension of Bental and Ravid (1982), and which implies that the cost of outages may be inferred from revealed preference data on generator expenditures. Fig. 5 presents schematically three possible outage cost developments to illustrate this concept.

As shown, the losses are inversely related to the amount of available backup generators. In scheme A, the relationship is linear, which means that each additional kilowatt-hour in backup capacity will reduce the loss by a constant amount. Schemes B and C show more realistic staircase type relationships between them. They model cases where the losses to the business occur in steps caused by phased thresholds. For example, floors have to be closed as a whole rather than as individual floor areas (see scheme C). Scheme B represents a case where the entire business shuts down at one threshold level.

The proxy method is, by far, the easiest to apply because the data requirements tend to be small compared with the other methods, and the data required for proxy measurements is relatively

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Table 3. Outage Cost Estimates (SEK/kW h) for Sweden (Andersson and Taylor 1986)

	0.5 h outage		8 h outage	
Area	1969	1980	1969	1980
Heavy industry	2.8	10.2	33.5	62.5
Households	5.0	1.0	72.5	62.5
Agriculture	6.3	2.0	92.5	56.0
Offices	6.3	26.0	100.0	451.0
Commerce	5.0	23.0	80.0	218.0
Railroads	4.8	8.2	51.5	89.9
Other transport	1.8	2.5	28.0	40.0
Urban areas	6.5	18.4	75.8	197.6
Rural areas	5.0	8.6	72.5	102.6
Entire country	4.0	8.8	—	111.8

easily obtained. However, using proxies will not give the best picture of the true costs of utility interruptions because they only provide upper and lower bounds. In addition to the disadvantages listed above, these methods do not allow for any differentiation. At best, the result may reflect average costs for an average customer. It is impossible to measure the effects of duration, frequency, time of day, etc., or to break costs down into categories.

Surveys

This is the primary source of information on outage costs because it is possible to find out how outage costs vary with outage characteristics and to get a distribution of outage costs over the target population, unlike the other methods, which do not allow this type of differentiation. Caves et al. (1990) discuss several major types of surveys.

The first major type of survey is the direct cost survey. Utility customers are asked to place a dollar value on the costs they would incur during an interruption in service. This type of survey is likely to yield good results for industrial and commercial customers, especially if they have had some direct outage experience. Residential customers, on the other hand, are unlikely to be able to give a very accurate estimate of the costs that they would incur, because most of their costs would not be valued in the market, and they probably have not spent much time thinking about the potential costs of an outage compared with commercial and industrial firms.

Table 3 presents a study done in Sweden that compares estimated outage costs for different customer groups and outage duration in 1969 to estimates for 1980. As one can see, major shifts took place between 1969 and 1980. For example, outage costs for households and agriculture fell while the outage cost for offices and commerce quadrupled. It is also apparent that some customers had sharp increases in outage costs if the outage lasted for more than 2 h (e.g., agriculture.)

Contingent valuation surveys ask utility customers about their willingness to pay (WTP) or willingness to accept (WTA), contingent on there being a market in which to trade. Therefore, all payments or receipts are purely hypothetical. For WTP, customers are asked how much they would be willing to pay in order to avoid an outage or to obtain increased reliability. Under WTA, the survey asks customers how much they would have to be compensated in order to accept a reduction in service reliability or to keep the current level of reliability instead of an increased reliability level.

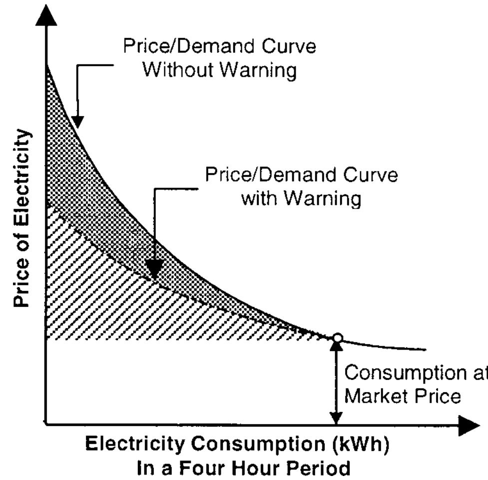

Fig. 6. Outage cost based price elasticity (Sanghvi 1982)

A third survey method is the contingent ranking method, in which customers are asked to rank a series of outage options, with each option accompanied by a rate increase or decrease. From the responses given, WTP and WTA can be inferred using discrete choice models of customer preferences.

Market-Based Methods

With these measures, writers have attempted to avoid the problem of limited data on customer choices among different levels of service reliability. Since most utilities have only limited experience with rate and service options providing different levels of reliability, researchers attempt to use information on customer response to price changes in order to infer the value of reliability. Fig. 6 presents two demand curves which both begin at C, representing the electric consumption at the beginning of an outage. As shown, the hypothetical demand curve without advanced warning is steeper then the curve with warning. The area underneath a curve represents the total loss to the electricity supplier.

For damages to utility lines due to a construction accident, we can assume that there would be no warning at all before a power outage. Therefore, the relatively inelastic demand curves corresponding to the very short run should be used to calculate the damages. The problem is that current estimates of demand curves for electricity are based on price changes known well in advance. Because the demand curves being used to derive outage costs are not the same as the demand curves customers face when their power is cut without warning, outage costs would tend to be understated.

In Caves et al. (1990), only the residential sector has any studies using consumer surplus. In these studies, Gilmer and Mack (1983) and Sanghvi (1982) both find the value of outage costs to be only slightly greater than zero in 1986 $/kWh unserved. For the industrial sector in Israel, Grosfeld-Nir and Tishler (1993) found expected outage costs ranging from $4.04 in 1987 $/kWh unserved to $20.31 in 1987 $/kWh unserved, depending on the industrial branch using their stochastic market-based model.

Based on the data provided in Table 4, the industrial branches with the highest outage costs in their study were clothing and electronics. On the other hand, mining and quarrying had the lowest outage costs. In general, the outage costs are heavily dependent on the consumers' activities, the degree to which the affected activities depend upon the impacted utility, the availabil-

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Table 4. Expected Outage Costs ($) per Lost Kilowatthour in Israel for 1987 (Tishler 1993)

Industrial sector	Output loss	Production loss	Material damage	Total
Chemical and oil	0.78	0.66	2.50	3.94
Electronics & electricity	4.83	3.35	3.57	11.75
Metal	2.17	1.66	2.79	6.62
Nonmetallic minerals	0.97	0.78	2.24	3.98
Clothing	8.48	5.86	7.76	22.10
Transport equipment	3.58	2.55	3.24	9.37
Food/beverages	1.40	1.07	2.74	5.21
Mining/quarrying	0.56	0.49	0.33	1.38
Textiles	0.93	0.75	1.65	3.33
Rubber and plastic	1.43	1.10	3.97	6.50
All others	2.70	2.00	4.08	8.78

ity of backup sources, and the speed and extent to which customers can resume normal activities following the restoration of the utility service. Therefore, important variables in determining the total service disruption costs include the time of occurrence, duration, magnitude, frequency, warning time and area affected (Sanghvi 1982).

1. The time of occurrence is significant because disruptions are much more costly at some times than others. A disruption in the middle of the night will affect some industrial customers involved in production three shifts per day, but may leave the majority of customers almost entirely unaffected. On the other hand, an outage during peak business hours or seasons may be extremely costly, even if only a brief duration.
2. The duration of the interruption is very important in determining costs because there are many losses which depend on the length of time without service. If a firm suffering a service interruption normally produces a certain amount of output per day, the higher the portion of day lost, the greater the output loss is expected to be, although the relationship may be highly nonlinear (see Table 3).
3. Magnitude is a measure of the amount of service lost (e.g., kilowatthour for electricity), so the cost of an outage should be expected to increase as the magnitude increases because there is a larger amount of utility service which customers would choose to buy but cannot. Assuming that the utility is being used as an input in either industrial, commercial or residential production, as more of the utility is lost, more production will be lost.
4. The frequency of interruptions has an effect because the more frequent the disruptions, the more likely that customers will purchase backup protection. Therefore, as the frequency of disruptions increases, the costs associated with future disruptions may actually decrease as a result of the increased level of backup protection (Sanghvi 1982). Conversely, Tishler (1993) finds that the more reliable the electricity system becomes, the more costly outages become, again because of the effect on the amount of backup protection present.
5. The warning time is significant because the more warning there is, the more easily households and firms can adjust their schedules around the service interruption, lowering the costs of the interruption. Since this paper is only concerned with accidental damages to utilities, the warning time for these cases will generally be zero. The interruption will likely occur instantaneously when the line is damaged, and individual accidental damages cannot be anticipated by definition.

Table 5. Loss Increases (SEK/kWh) for Sweden in 1980 (Andersson and Taylor 1986)

Area	0.5 h outage	2 h outage	8 h outage	Total increase (%)
Heavy industry	10.2	23.5	62.5	613
Households	1.0	5.4	62.5	6,250
Agriculture	2.0	9.3	56.0	2,800
Offices	26.0	107.0	451.0	1,735
Commerce	23.0	62.0	218.0	948
Railroads	8.2	24.5	89.9	1,096
Other transport	2.5	10.0	40.0	1,600
Urban areas	18.4	52.6	197.6	1,074
Rural areas	8.6	22.9	102.6	1,193
Entire country	8.8	27.2	111.8	984

6. The area affected will be important because it defines the customer base. The impact will be very different in an industrial park than in a residential subdivision. The costs incurred as well as their magnitudes will be very different depending on what type of area was affected.

Table 5 shows the disproportional effect of outage duration on various customers in Sweden for 1980. As one can see, households show steep increases of 540% when the outage lasts 2 h instead of 0.5 h and another 1,157% when the outage lasts 8 h. The dramatic increase may be the result of situations where the effect in not seen immediately. For example, refrigerated and frozen items will not spoil immediately, but as a power outage continues long enough to reach a certain duration, these items will begin to spoil. Other customers that were hardest hit are agriculture and offices.

As demonstrated, several models for costing consequential cost of electric outages do exist. Although they are not directly applicable to other utilities, they provide the primary framework that could be adapted to the specific characteristic of each. The final section of this paper will provide a short presentation of the concept that could lead to an extended version of the framework.

Economic Impact Model

Following the existing categorization of cost into direct and consequential, a two-tiered cost pyramid emerges. As graphical representation in Fig. 7 shows, similar to the circular waves caused by a stone thrown into the water, an accident is surrounded by two main rings.

Each ring, or cost category, is broken down into various cost accounts, not intended to be comprehensive. The first ring lists five accounts commonly referred to as direct costs of an accident: (1) emergency services, (2) death/injury, (3) repair, (4) property damage, and (5) losses in time and material. From the perspective of a company, some of these costs may be considered indirect, but from the viewpoint of the accident they can be considered direct.

The second ring contains ten consequential cost accounts. Again, not comprehensive, they are discussed in the following section.

Accounting for Consequential Costs

The list of parties impacted by a disruption reaches far beyond the utility itself to include families of killed or injured persons, property owners whose property might be damaged, people living in the vicinity of accidents requiring evacuations, and the many cus-

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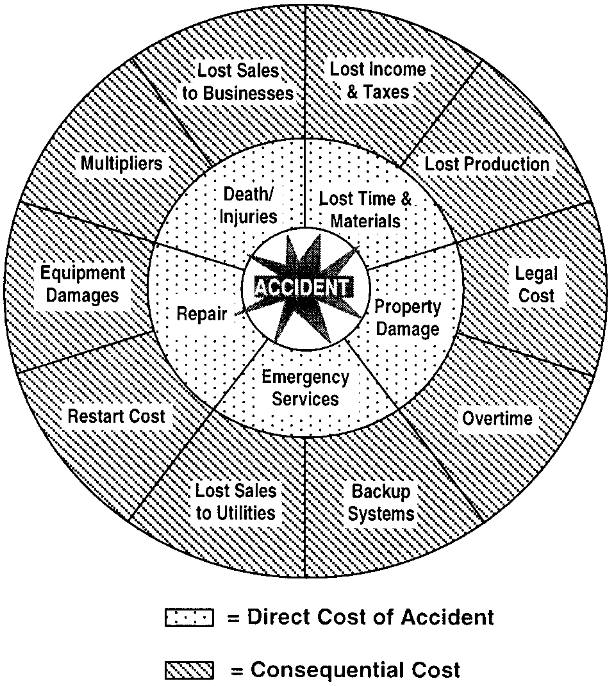

Fig. 7. Two-tiered damage cost structure

tomers that might experience a cutoff. The customer groups include: (1) private homes, (2) governmental agencies, (3) service companies, (4) schools, (5) hospitals, (6) industrial firms, (7) transportation systems like airports, taxi services, freight trains and trucking, (8) retailers, and (9) utilities, themselves. As will be shown in the next section, even this list is incomplete, since evacuations due to a gas leak may impact organizations that do not even use gas. The following is a discussion of generic consequential cost accounts that may be valid in one or more user groups.

Lost Production

Utility outage will require firms to make adjustments in their production schedule, thereby, creating several types of costs. In severe cases, production might be permanently lost. The cost of net lost production will depend on: (1) type of production, (2) outage duration, (3) time of occurrence, (4) number and kind of customers, (5) magnitude of outage, (6) the ability of firms to substitute production across time, (7) season in which the outage occurs, and (8) the backup system capacity which firms possess. If an industrial customer uses natural gas only for heating, and service is interrupted in the middle of summer, the cost is negligible. However, if the same interruption occurs in the middle of winter, it may become too cold for workers to operate at normal productivity levels.

Equipment Damages

As everybody who owns a modem knows, surges in power and telephone line can cause costly repairs to the computer hardware. Similarly, power interruptions may cause damage to sensitive electronics, or mechanical equipment within industrial plants, when stopped in the middle of a continuous batch process. For example, when working with molten materials, a power outage may cause the process materials to harden.

Restart Costs

Many processes require machinery to be readied or calibrated or the initial units produced will not meet specifications and are, therefore, discarded. Restart costs can be avoided or minimized if utility substitution, such as gas to electric, is possible, or if a backup source, such as gas generators for electric power, is available. It is apparent that such measures will result in other costs, however.

Deployment of Emergency Backup

Many customer groups train and maintain an emergency response unit to be available in the case of a utility outage. For example, banks have to back up sensitive information from their computer systems, while manufacturing plants deploy an emergency crew for shutting down or cleanup. These crews have to be called up and rapidly put in place at any time.

Multiplier Effects

Because Just-in-Time materials management is being applied more and more, firms that depend on products from an impaired firm can be affected as well. Lack of key materials in stock will cause delays and downtime of their own while waiting to be resupplied by the suppliers. In less developed countries where outages are frequent, the impact on the economy is very large. In the case of Pakistan, Pasha et al. (1989) estimate that the multiplier was equal to 1.34 for 1984–1985, meaning that inclusion of a multiplier effect increases production costs by as much as 34%. They calculate that the Pakistani gross domestic product lost 1.8% due to outages.

Commerce

It is very hard to aggregate among commercial firms because the commercial sector encompasses so much economic activity. Commercial firms will tend to have higher outage costs in the case of a communications outage. In addition, commercial firms will tend to be less likely to have backup systems than industrial firms because they do not have to be as concerned about machinery damage, spoilage, or restart costs. As a result, they have less of an incentive to invest in backup systems and outages will result in higher costs per kilowatt hour than for industrial firms.

Disruption of Household Activities

This is the major cost normally assumed by residential utility customers (Yabroff 1981; Sanghvi 1982; Sarkar 1991). In some studies of the residential costs of outages, it is assumed that all household production and leisure is entirely lost during an outage. However, this is not likely to be the case because these consumers are free to substitute towards activities which do not require the lost utility service. For example, instead of washing clothes or cooking on the stove, consumers without gas or electricity may choose to work in the yard, or run errands outside the home, or engage in any other activity that does not require the use of the lost utility service. Gas heat is important in some regions during winter, but not at all during the summer. Most telephone calls can probably be made at a later time without much loss, though there may be emergency calls or electronic mail that needs to be delivered at a specific time. Even then, cellular service or other communication technologies may be substituted for the interrupted service, if available.

Summary and Conclusion

In TEA 21, the congressional Transportation Equity Act for the 21st Century, it is noted that the public, businesses, and critical

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public services such as air traffic control are experiencing significant negative effects from accidents involving our utilities. The Common Ground Report (U.S. Department of Transportation 1999) calls for collective effort: "Protecting this essential infrastructure is a top priority for the people who plan, install, operate, repair, and regulate underground facilities." This paper presents the result of an effort towards establishing a mathematical base for an approach that uses an economic concept to define how much protection our infrastructure deserves.

Despite the successful implementation of one-call systems in most states of the U.S., accidents caused by damaging underground utilities are extensive, resulting in clogged residential sewer lines all the way to gas explosions that cause death and destruction. This paper argues that a mathematical optimization method based on marginal cost should be used as a means to set goals. Here, the key premise is that it is economically prudent to invest in utility protection as long as $1 of extra expenditure for prevention results in at least $1 of savings from damage reduction. However, the analysis of a real incident showed that the present accounting of damages drastically underreports the actual cost, referred to as economic impact cost. The reason for this underreporting is the difficulty of assessing consequential cost for the multitude of utilities, customers, and regional difference, as well as the practice of companies not to publish their costs for competitive reasons. As a result, the author proposes to circumvent this serious obstacle by adapting tested economic models used worldwide to assess the impact of power outages. This will, without a doubt, require an extensive effort leading to the establishment of a large data base that ensures statistical validity. On the other hand, the cost and the frequency of interrupted business and commerce might continue to rise, making it necessary to declare underground utilities a national asset deserving protection from humans.

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