Chapter 17

A FRAMEWORK FOR MODELING INTERDEPENDENCIES IN JAPAN'S CRITICAL INFRASTRUCTURES

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Abstract This paper discusses Japanese efforts related to critical infrastructure protection, including several case studies to clarify the risk components and countermeasures. An interdependency modeling framework that combines the inoperability input-output model (IIM) for economic interdependencies and Bayesian networks for operational dependencies is presented. Also, the paper provides new multidimensional measures for interpreting interdependency modeling results.

Keywords: Japan, interdependency modeling

1. Introduction

The modeling and analysis of critical infrastructure interdependencies are challenging tasks. Traditionally, these tasks have been performed using qualitative and/or quantitative approaches. Qualitative approaches typically rely on expert knowledge and experience, often gleaned from interviews and expressed in loosely-structured terms. Nevertheless, these approaches have been used to good effect, especially when the expertise pertaining to critical infrastructure assets is engaged in a systematic manner. Quantitative approaches, on the other hand, often engage national input-output statistics for critical infrastructure dependency assessments. However, these statistics have certain limitations when they are used to analyze interdependencies existing between multiple critical infrastructures.

This paper discusses Japanese critical infrastructure protection efforts with an emphasis on interdependency analysis. Several case studies are presented to clarify the risk components related to Japan's critical infrastructures and the associated countermeasures. A framework for interdependency modeling that combines the inoperability input-output model (IIM) for economic interdependencies and Bayesian networks for operational dependencies is presented. Also,

Table 1. Critical infrastructure sectors in Japan and the United States [7].

Japanese CI Sectors	United States CI Sectors
1. Government Services	1. Government Facilities
2. Communications (and Broadcasting)	2. Communications
3. Finance (and Insurance)	3. Banking and Finance
4. Air Transportation	4. Transportation Systems
5. Railway System	5. Energy
6. Electric Power	6. Public Health and Health Care
7. Gas	7. Water
8. Medical Services	8. Dams
9. Water Supply	9. Agriculture and Food
10. Logistics (Road Transportation not incl. Private Transportation)	10. Chemical
	11. Commercial Facilities
	12. Emergency Services
	13. Information Technology
	14. Postal and Shipping
	15. Nuclear Reactors, Materials and Waste
	16. Defense Industrial Base
	17. National Monuments
	18. Critical Manufacturing

the paper specifies new multidimensional measures for interpreting interdependency modeling results.

2. Overview

Table 1 lists the Japanese and U.S. critical infrastructure sectors. Note that only ten sectors are identified as being critical in Japan as opposed to eighteen sectors in the United States. Earthquake-prone Japan has extensive experience dealing with natural disasters. Japan's well-established emergency management and disaster recovery practices have been naturally extended to critical infrastructure protection. Consequently, in the Japanese context, most critical infrastructure protection efforts engage existing anti-disaster measures articulated via "system of systems" approaches. Note, however, that critical infrastructure protection is distinguished from emergency management and disaster recovery efforts by emergent information technology (IT) threats.

The Japanese National Information Security Center (NISC) was established in April 2005 as the central coordinating entity for IT security efforts. NISC has four crucial functions [17]: (i) planning fundamental government-wide strategies for IT security policy; (ii) promoting comprehensive security measures for government agencies; (iii) providing incident handling functions for government agencies; and (iv) enforcing critical information infrastructure protection. NISC

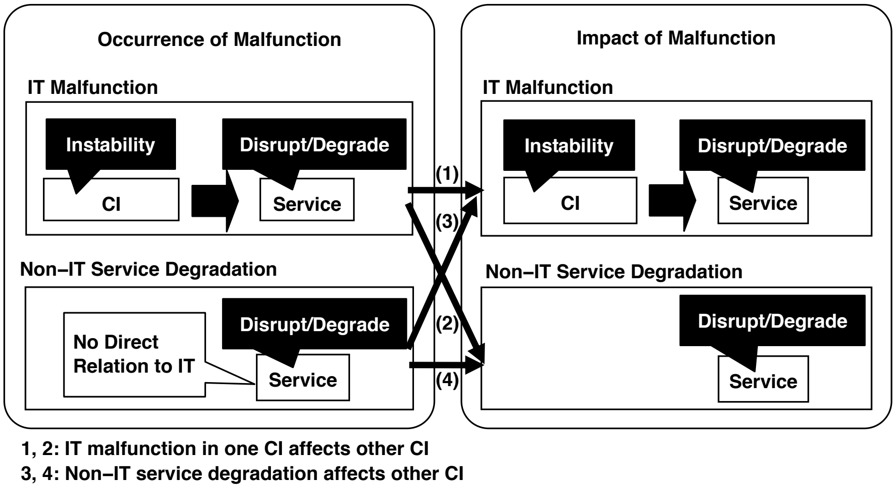

Figure 1. NISC interdependency analysis scope [7].

also coordinates information exchange between the various Japanese stakeholders as well as foreign entities.

One of the principal NISC committees is the Critical Infrastructure Technical Committee, which has 26 members from industry, research organizations, academia and government. A 2007 study by the Technical Committee [7] confirmed the propagation of adverse effects of disruptions or malfunctions in one critical infrastructure sector to other sectors.

Figure 1 illustrates the scope of the interdependency analysis conducted by the NISC Technical Committee. The occurrence of an IT malfunction in one or more critical infrastructure sectors can cause service disruptions and/or degradation in other sectors. Services that have no direct relation to IT can also be degraded. Consequently, the Technical Committee emphasized the importance of comprehensively analyzing the interdependencies existing between the ten critical infrastructure sectors.

Of the ten critical infrastructure sectors in Japan, broadcasting, railway system, electric power, gas, medical services, water supply and logistics are termed as highly-independent (robust) systems. On the other hand, communications, finance, air transportation and government services are termed as low independence (weak) systems. Note that communications and broadcasting is defined as a single sector. However, they are treated separately because of their different dependency characteristics.

Figure 2 presents the results of the interdependency analysis conducted by the NISC Technical Committee [7]. The dark circles represent sectors with low independence; the dotted arrows represent time-varying dependencies. Note that communications, electric power and water supply are the major supporting sectors for many other critical infrastructure sectors. Electric power plays the largest role in supporting other critical infrastructures. Communications

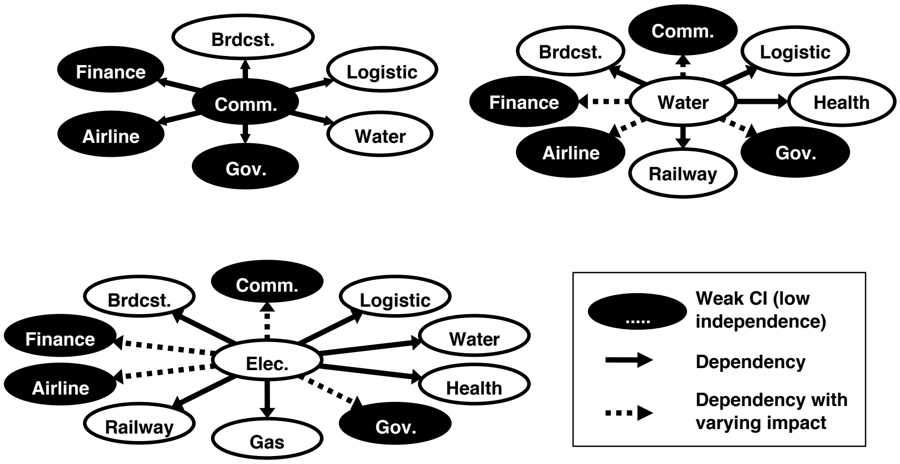

Figure 2. Interdependency analysis results [7].

has a smaller role compared with electric power, the reason being that some sectors (e.g., the railway system) use their own communications networks for operations and do not rely on the public communications network. Consequently, a public communications network disruption has little, if any, impact on these infrastructures. Nevertheless, it is important to note that all the dependencies on the communications sector are direct dependencies (arrows) that represent high vulnerability.

3. Risk Components

The prototypical expression for risk in the homeland security context is written as:

$$Risk = Threat \times Vulnerability \times Consequence$$

where the total risk is the combination or the Cartesian product of all relevant threat types, system weaknesses (vulnerabilities) and consequences that occur when the damage-inducing mechanisms associated with the threats interact with the vulnerabilities [6]. This section discusses a number of case studies along with the various risk components – threats, vulnerabilities and consequences – in the context of Japan's critical infrastructure sectors. Figure 3 outlines the various discussion points.

3.1 2004 Niigata Chuetsu Earthquake

The Niigata Chuetsu earthquake occurred at 5:56 p.m. on October 23, 2004 (Saturday) in an isolated mountainous region. A total of 48 fatalities and 643 serious injuries were reported [11]. Approximately 278,000 households lost electricity, water and gas supply. Cell phone service was disrupted as a result

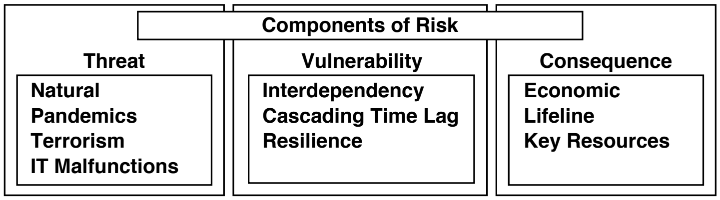

Figure 3. Risk components in Japan's critical infrastructures.

of the power outage (backup systems for cell towers only supply power for one day).

The most notable case was the first-ever derailment of a high-speed bullet train. The main shock occurred as the northbound train traveling in excess of 200 km/hr was exiting a tunnel just south of Nagaoka. The bullet train took more than 1.5 km to stop; fortunately, no injuries resulted from the derailment. The Joetsu Shinkansen line, which carries 360,000 passengers per day, was out of service until early 2005 [11]. The Tokyo Stock Market dropped considerably on the Monday following the earthquake, with Japan Rail East suffering large stock losses. This highlights the societal interdependence with the economic sector.

Table 2. Operational levels at 217 manufacturing plants.

Operational Level	**0%**	**≤50%**	**≤70%**	**≤100%**	**100%**
November 4, 2004	24 (11%)	19 (9%)	21 (10%)	48 (22%)	105 (48%)
November 15, 2004	2 (1%)	7 (3%)	15 (7%)	39 (18%)	154 (71%)
December 1, 2004	0 (0%)	4 (2%)	3 (1%)	17 (8%)	193 (89%)

The Niigata Sanyo Electronic Semiconductor plant with 1,500 workers was closed until December 22, 2004. The shutdown cost the parent company 50 billion yen in direct losses and 37 billion yen in indirect losses. The Nihon Seiki automobile parts plant was unable to resume its motorcycle speedometer assembly line, which caused Honda Motor Company to halt production at four plants elsewhere in Japan; Yamaha Motor Company was also affected [8]. Table 2 shows the changes in operational level (as a percentage of operations before the earthquake) for 217 manufacturing plants in the region at three different times after the earthquake.

3.2 2007 Chuetsu Offshore Earthquake

The Chuetsu offshore earthquake (magnitude 6.6) occurred at 10:13 a.m. local time on July 16, 2007 in the Niigata region. Eleven deaths and at least 1,000 injuries were reported; 342 buildings were completely destroyed, mostly older wooden structures [3].

The Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP), the world's largest nuclear power generation facility, which is owned and operated by the Tokyo Electric Power Company (TEPCO), was affected by the earthquake. KKNPP produces power for approximately 30 percent of Japanese homes [2]. The earthquake started a small fire at the sprawling Kashiwazaki-Kariwa nuclear complex and caused 312 gallons of radioactive water from the plant to spill into the Sea of Japan. TEPCO did not announce the leak until nearly 12 hours after the earthquake struck. On July 18, TEPCO announced that the leak was actually 50% more radioactive than originally estimated [15]. The plant was closed for testing [16] and remained completely shut down for more than twenty months after the earthquake. The area, ordinarily with a strong tourism industry in the summer months, was hit hard by cancellations due to fears about the nuclear plant. This highlights the policy/procedural interdependence and the societal interdependence with the economic sector.

Two days after the earthquake, Toyota announced that it would stop production at all its factories for the rest of the week because of the damage to the Riken automobile parts plant in Kashiwazaki, Niigata. Nissan shut down two of its factories; Mitsubishi Motors and Fuji Heavy Industries also scaled back production [13].

3.3 1995 Tokyo Subway Gas Attack

At 8:15 a.m. on March 20, 1995, three Tokyo subway lines were simultaneously affected by the release of lethal Sarin gas by the Aum Shinrikyo cult. Twelve people died and 5,000 were injured, most of them with long-term health consequences. Post-attack police raids led to the discovery of several tons of chemicals, enough to kill more than four million people [18].

Japan has not faced any bioterrorism-related events since the Aum Shinrikyo attack. However, several willful attacks have been executed by individuals. One of the worst attacks occurred on June 8, 2008 [4]. Tomohiro Kato, 25, hit three people with a two-ton truck near Akihabara Station, Tokyo. He then jumped on top of one of the men he had hit with his vehicle and stabbed him several times. He proceeded to walk towards Akihabara Train Station slashing pedestrians at random, eventually killing seven people and injuring ten others. Because of Japan's densely-populated cities and crowded stations, bioterrorism or any other type of willful attack on the public can lead to a significant number of casualties.

3.4 2005 Tokyo Stock Exchange Failure

On November 1, 2005, a problem with newly-installed software designed to improve the Tokyo Stock Exchange's ability to deal with higher trading volumes shut down the exchange for almost an entire trading day. On December 8, 2005, a trader at Mizuho Securities issued an order to sell 610,000 shares of J-Com (a job recruiting company) at 1 yen a share. The intention was to sell one share at 610,000 yen (approx. $5,000). Mizuho Securities personnel discovered the error within 85 seconds of the order being placed and made four attempts to cancel it, but the attempts were rejected by the Tokyo Stock Exchange. Mizuho Securities finally managed to buy back most of the erroneous order.

Upon consulting with Fujitsu, the system vendor, the Tokyo Stock Exchange found that the system was unable to cancel sell orders while taking buy orders. Nor was the system programmed to accept cancellation orders on newly listed stocks. Investors purchased about 100,000 of the nonexistent shares, which resulted in a loss to Mizuho Securities of about $225 million to reimburse buyers and cancel the order [5, 14]. Cyber attacks and natural disasters are the primary concerns as far as critical infrastructures are concerned. However, human error, system flaws and improper procedures can also lead to disastrous effects.

3.5 Other Events

The following are some of the other key incidents recorded in Japan since 2002:

- Dam break (2002)
- Banking system integration malfunction (2002)
- Air traffic control system malfunction (2003, 2008)
- Nationwide ATM network malfunction (2004)
- IP telephony interruption (2004)
- Fire department emergency number outage (2004)
- Erroneous tests on hepatitis virus infected blood (2005)
- Securities trading system malfunction (2005, 2006, 2008)
- Airline check-in system malfunction (2007)
- Railway automatic ticket gate malfunction (2007)
- Newspaper printing system malfunction (2007)
- Railway routing control equipment malfunction (2008)
- Public telephone communications malfunction (2008)

3.6 Generating Potential Scenarios

Based on the incidents described above, we provide some scenarios that define the scope of our study. Note that it is important to distinguish between the terms "common failure" and "interdependency." In the case of a natural disaster (e.g., an earthquake), multiple critical infrastructures are affected due to a common failure. In contrast, an interdependency between critical infrastructures leads to a cascading failure due to the networked infrastructures. Scenarios of interest include:

- A strong earthquake affects a major national highway and restoration work requires several days.
- A power plant is destroyed by a severe typhoon resulting in insufficient power supply to an urban area.
- An attack at a Tokyo station disrupts railway service.
- A flood contaminates the water supply system and cleaning efforts require several days.

4. Modeling Interdependencies

This section describes an interdependency modeling framework that combines the inoperability input-output model (IIM) for economic interdependencies and Bayesian networks for operational dependencies.

4.1 Inoperability Input-Output Model

Leontief received the 1973 Nobel Prize for Economics for developing his input-output model of the economy. Leontief's model facilitates the analysis of the interconnectedness between various sectors of an economy and the forecasting of the effects of a change in one economic sector on another. The inoperability input-output model (IIM) based on Leontief's seminal work was developed by Haimes and co-workers [1, 9]. The IIM formulation is given by:

$$q = A^*q + c^* = (I - A^*)^{-1}c^*.$$

The terms in the IIM equation are defined as follows:

- q is the inoperability vector expressed in terms of normalized economic loss. The elements of q represent the ratio of unrealized production (i.e., "business-as-usual" production minus degraded production) with respect to the "business-as-usual" production level of the industry sectors.
- A^* is the interdependency matrix that indicates the degree of coupling of the industry sectors. Each element indicates how much additional inoperability is contributed by the column industry to the row industry.
- c^* is a demand-side perturbation vector expressed in terms of the normalized degraded final demand (i.e., "business-as-usual" final demand minus actual final demand divided by the "business-as-usual" production level).

Interested readers are referred to [10] for details about the derivation of the model and the model components.

Table 3. Total requirements of Japan's ten CIs (2000) [12].

	Elec.	**Gas**	**Water**	**Finance**	**Rail**	**Logistics**	**Air**	**Comm.**	**Gov.**	**Med.**
Elec.	1.043578	0.025498	0.093584	0.0082	0.060693	0.011241	0.015587	0.015551	0.017824	0.02493
Gas	0.000534	1.012813	0.001717	0.001005	0.001095	0.000808	0.001316	0.001071	0.001191	0.003883
Water	0.001937	0.005211	1.105431	0.002248	0.006977	0.002976	0.003473	0.004135	0.004786	0.007713
Finance	0.059927	0.029559	0.034154	1.099556	0.232122	0.038274	0.071628	0.046012	0.020523	0.037563
Rail	0.002233	0.002142	0.00242	0.009354	1.003249	0.002407	0.002884	0.002962	0.006447	0.004207
Logistics	0.012923	0.020586	0.011587	0.008528	0.006226	1.006349	0.007863	0.015381	0.010985	0.013164
Air	0.000791	0.00063	0.000836	0.001372	0.000626	0.000505	1.005925	0.002804	0.001273	0.001525
Comm.	0.012735	0.016381	0.018865	0.032934	0.017441	0.015884	0.021257	1.154597	0.021695	0.017611
Gov.	0.00123	0.00131	0.001932	0.001498	0.000911	0.001205	0.002105	0.001109	1.00044	0.000994
Medical	0.000007	0.000024	0.000054	0.000034	0.00003	0.000004	0.000006	0.000049	0.000014	1.0233

The foundation of IIM is the interdependency matrix A^* derived from the Leontief coefficients. IIM has been shown to be very effective for the *post facto* estimation of economic losses and for risk management decision making [1, 9]. The primary limitation of IIM with regard to critical infrastructure modeling is that economic dependencies rather than operational dependencies are employed. In addition, IIM, which is based on Leontief's economic model, requires a system to return to equilibrium. Since returning to the equilibrium state can take some time, IIM cannot deal with cascading latency and resilience that occur within short time periods. Moreover, most critical infrastructures are utility systems that have low economic values in input-output tables.

Table 3 presents the total requirements for the ten Japanese critical infrastructure sectors. For example, producing one unit of water (column) requires 0.093584 units of electricity (row). Note that each table value indicates the total (i.e., direct plus indirect) amounts of materials needed to produce a product (e.g., an indirect amount is the amount of material needed to produce the raw materials used to produce a product). An examination of the total requirement values reveals that the economic dependency and operational dependency are considerably different. For example, in previous operational dependency analy-

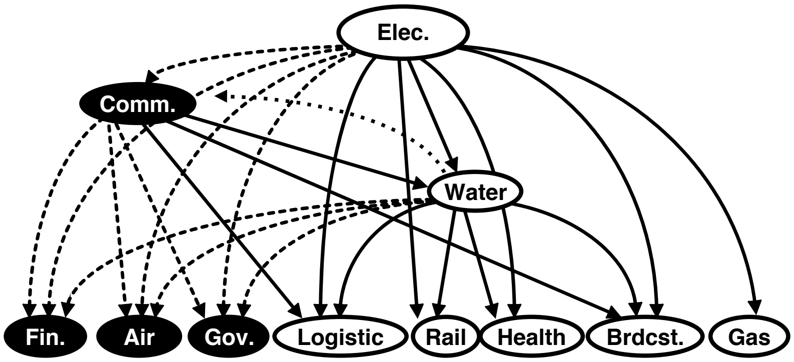

Figure 4. Dependency network for external perturbations of the electricity system.

ses conducted by the NISC Technical Committee, the financial sector was never a major contributor. However, from the economic point of view, the financial sector is clearly a major contributor to practically every critical infrastructure sector. Because of these limitations, we use a Bayesian network to model the operational dependencies existing between the ten critical infrastructure sectors and use the Bayesian network output as an external perturbation for IIM to estimate the total loss for all sectors.

4.2 Bayesian Networks

A Bayesian network is a probabilistic model that represents a set of variables and their probabilistic dependencies. The networks are quite effective and easy to maintain for a small number of nodes such as the ten critical infrastructure sectors.

Bayesian networks provide efficient representations of domain knowledge pertaining to dependencies, especially when combined with well-structured questionnaires and knowledge eliciting processes. The conditional probability values in these networks are flexible enough to express cascading latency and external interventions. However, the primary limitation of Bayesian networks is that they do not permit bilateral dependencies (e.g., the interdependency between the communications and water supply critical infrastructure sectors). Bayesian networks can express backward causal dependencies, but these are not useful for our purposes. To address the limitation, separate Bayesian networks are used for the major contributing critical infrastructure sectors. Additionally, certain adjustments have to be made in the case of interdependent systems.

Figure 4 shows the dependency network constructed from the results of the NISC Technical Committee's interdependency analysis described in Section 2.

Figure 5 shows how operational dependencies between critical infrastructures can be calculated before using IIM to estimate losses for all the critical infrastructure sectors.

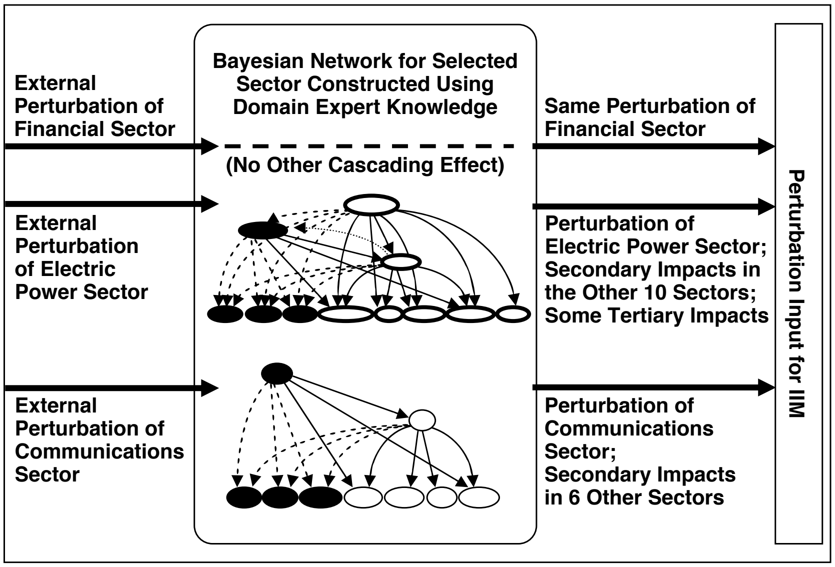

Figure 5. Calculating distributed operational impact before IIM.

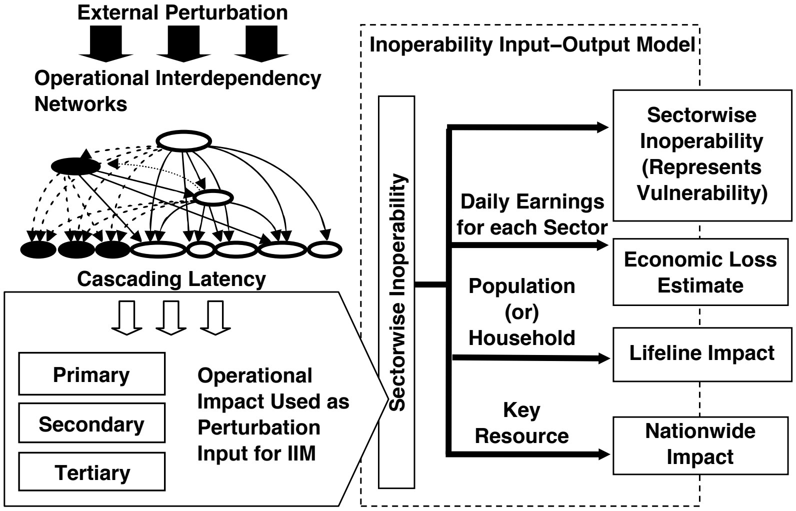

Figure 6. Modeling framework for interdependent CIs.

4.3 Modeling Framework

Figure 6 illustrates our framework for modeling critical infrastructure interdependencies. The first task is to conduct a survey to obtain information about the operational dependencies of critical infrastructure sectors and to construct Bayesian networks for three sectors – communications, electric power and water supply – that have major contributing roles. The survey questionnaires should focus on understanding the level of inoperability in each of the ten critical infrastructures caused by disruption/degradation of service in the sectors. Also, it is necessary to identify the sectors that are the major contributors to critical infrastructures with low independence (i.e., weak systems such as communication, finance, air transportation and government services). The resulting distributed impacts to the ten sectors can be used as external perturbation inputs for IIM.

National input-output tables for Japan are available from the Statistics Bureau of the Ministry of Internal Affairs and Communication [12]. The data are provided in three aggregated forms: sector tables (13 sectors); major consolidated sector tables (32 sectors); and intermediate consolidated sector tables (104 sectors). It is best to use the consolidated sector tables (104 sectors) in the interdependency and inoperability computations because they contain the information related to the ten sectors of interest.

An intra-regional coefficient matrix is used to express the inter-sector dependencies for the nine major regions in Japan. The Ministry of Economy, Trade and Industry has complied intra-regional, inter-sector input-output tables and inverse matrix coefficient tables for each of the nine regions (for the year 2000). The tables, which are provided at four levels of aggregation (12, 27, 52 and 75 sectors), are available for:

- Hokkaido (www.hkd.meti.go.jp/hoksr/h12renkan/12renkan.htm)
- Tohoku (www.tohoku.meti.go.jp/cyosa/tokei/io/io12nenn/12nenhyo_hombun.htm)
- Kanto (www.kanto.meti.go.jp/tokei/hokoku/20041214iohyo12.html)
- Tokai (www.chubu.meti.go.jp/tyosa/io7/io.htm)
- Kinki (www.kansai.meti.go.jp/1-7research/I-O/kinkisangyouren.html)
- Chugoku (www.chugoku.meti.go.jp/stat/io/h12io/h12.htm)
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- Okinawa (www.pref.okinawa.jp/toukeika/io/2000/sanren_top.html)

The fundamental problem is to answer three questions given a set of external perturbations and cascading latency:

- What are the cascading inoperability and potential economic losses?
- Which critical infrastructures should be strengthened to yield optimal economic loss reduction or improvement in resilience?

- Which critical infrastructures will expose severe vulnerabilities in the event of unexpected inoperability escalation?

The combination of IIM and Bayesian networks facilitates the flexible incorporation of cascading latency and risk management intervention. The framework offers an interactive view of critical infrastructure interdependencies by providing the real-time inoperability of a critical infrastructure and a potential economic loss estimate for every adjustment (i.e., risk management decision).

4.4 Interpretation of Model Outputs

Most input-output models are used to estimate the economic losses of disasters. However, we believe that sectorwise inoperabilities can be used to obtain better assessments of disaster impact (Figure 6).

The inoperability values represent sectorwise vulnerabilities. They provide significant information about the most inoperable sectors to decision makers, which would otherwise be overlooked because of their insignificant contributions to economic impact.

The first metric is a sectorwise economic loss that can be generated from the inoperability values. This metric is widely used to assess disaster impact. It is estimated by computing the regional daily production income for each sector [1] by dividing the regional GDP of the sector by 365 (days):

$$Loss(s_i) = q_i \times (Regional\ GDP_i/365).$$

Note that $Loss(s_i)$ is the economic loss in the ith sector, q_i is the inoperability of the ith sector, and $Regional\ GDP_i$ is the regional GDP of the ith sector.

The sum of the individual sector losses yields the daily economic loss estimate for a disaster. Multidimensional metrics used to describe disaster impact can enhance risk management decision making. In complex scenarios, such as earthquakes and cyber failures, no single metric adequately measures the impact. Describing only the economic loss due to an earthquake does not reflect the stressed situation because the economic measure does not capture suffering and despair.

Therefore, a useful second metric is an "affected population" value based on the inoperability matrix. This is computed by multiplying the population of the area impacted by the disaster with the maximum value of the inoperabilities of the lifeline support critical infrastructures:

$$P_{AFF} = P_{Area} \times Max(q_0, q_1, ...q_{ci})$$

where P_{Area} is the population of the area impacted by the disaster and q_{ci} is the inoperability of the ith lifeline support critical infrastructure. The result can be presented as radar chart (Figure 7) to assist in decision making.

The third metric is the impact of a disaster on national key resources such as the Shinkansen (bullet train) network, major highways, power plants, manufacturing plants, etc. A higher concentration of these key resources in a disaster-affected region can have a significant impact on the national economy. The

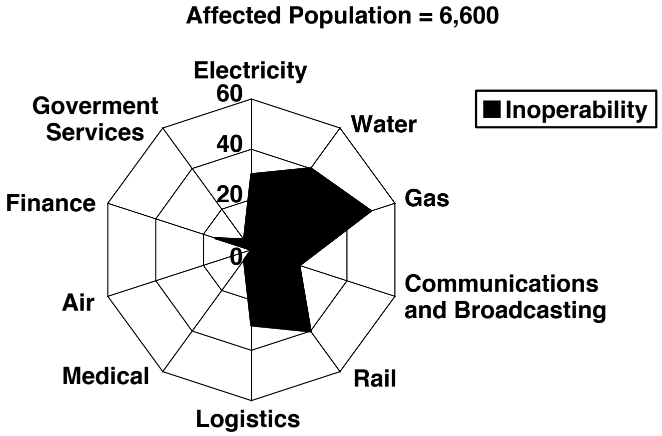

Figure 7. Lifeline disruption indicator.

national key resources should be well-documented and should have a uniform weighting system to yield useful impact assessments. The multiplication of a national key resource concentration index with the inoperability of the corresponding perturbed infrastructure can provide a useful estimate of the nationwide impact.

5. Conclusions

The modeling and analysis of critical infrastructure interdependencies are important research problems. The proposed framework combining IIM and Bayesian networks facilitates the incorporation of cascading latency and risk management intervention. The framework offers an interactive view of critical infrastructure interdependencies by providing the real-time inoperability of critical infrastructures and potential economic loss estimates for adjustments made as a result of risk management decisions. Our future research will conduct detailed analyses of the application of the framework to managing risk in Japan's critical infrastructure sectors. Also, it will focus on rigorous data analysis and model adjustment strategies.

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