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Chapter

Lifeline Interrelationships during the Tohoku Earthquake: Management of Disaster Analysis Reports Using Text Mining

Yasuko Kuwata

Abstract

Although many studies have been undertaken in the area of lifeline interrelation, examinations based on the quantitative evaluation of post-earthquake lifeline interrelations have been limited. In this study, we present a new methodology to evaluate lifeline interactions, with an emphasis on the aspects of earthquake disasters. Terms related to other lifelines used in disaster reports are somewhat influenced by post-earthquake behaviors. In this study, the number of related terms was counted, and the relationships between the lifelines were quantitatively assessed for the 2011 Tohoku earthquake that occurred in Japan. The validation process included checks through academic reports as well as government reporting. We found that many lifelines were strongly dependent on the electric power systems, which gave no consideration to the accident at the Fukushima nuclear power plant. We confirmed further that the similar lifeline interrelation results could still be obtained regardless of the reporting used.

Keywords: lifeline interrelation, Tohoku earthquake, disaster report, text mining, tsunami, blackout

1. Introduction

Damage to a lifeline system during an earthquake can cause widespread physical damage, with functional interruptions among systems causing many consequences. At the time of the 2011 Tohoku earthquake, strong ground motions were observed throughout a large portion of Japan, causing a large tsunami in the Pacific coast in 2011, with consequent lifeline damage expanded and spatiotemporally spread.

Other researchers, including Nojima and Kameda [1], had studied lifeline interrelations during an earthquake in the urban areas of Kobe in 1995. Based on these studies, the structure of lifeline interrelations was modeled systematically, with the interrelation structure additionally analyzed qualitatively based on the damage caused by the Kobe earthquake [2]. However, the interrelation over all lifelines had not yet been quantified at this time.

To date, only a few studies have modeled earthquake events of lifeline interrelations using system dynamics, which have attempted to quantitatively evaluate the impact on other lifelines by stopping the supply of one lifeline [3]. Although a part of the restoration process can be understood using this method, the model becomes

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more complicated when the interrelationship is explained as if the entire lifeline of the urban area is overlooked. If the model became complicated, multiple individual parameters are also required; thus, many assumptions may be involved to set the system correctly.

Nevertheless, there are indices which further quantify the influence of an earthquake on lifeline disruptions. For instance, the "resilience factor" of the Applied Technology Council document ATC-25 [4] was improved based on the "importance factor" proposed in the United States in ATC-13 [5]. The lifeline resilience factor, as defined by Kajitani et al. [6, 7], was additionally improved for the Japanese version of the resilience factor in ATC-25. In ATC-13, the importance factor was suggested on the basis of a questionnaire administered to 13 specialists regarding the influence of 1985 earthquakes in California. This factor ranged from 0 to 1, indicating a decreased rate of production for 35 different industries when each lifeline service was interrupted. However, these values were not based on the results of an actual earthquake. When this was applied to the affected areas in the 2004 Sumatra earthquake and tsunami, difference between the factor and the real results was observed, though the industrial type and scale were not the same as those of the ACT target set [8].

While several studies have been conducted on lifeline interrelation, as described above, only a few have focused on the quantitative post evaluations of lifeline interrelations after earthquakes, much less those which quantitatively appraise the entire lifeline before an earthquake. By using the report on the damage and restoration of lifelines after the Tohoku earthquake in 2011, this study relates the terms of other lifelines included in such reports to quantify lifeline system interdependencies and frequency-based incidents, proposing a new method to make this visible. Some studies have recently related the major research field of academic societies by way of text analysis [9].

Typically, the lifeline interrelation that occurs at the time of a disaster can change according to the type and scale of the hazard and the extent of each lifeline service outage. It has been considered that the extent of these influences is different for each earthquake shake; thus, it is necessary to examine the degree of hazard together with the lifeline outage. This study also aims to quantify the number of detected terms, as the meaning and usage of these terms and phrases are not always elucidated in detail. Therefore, while the value of the detection frequency has not always explained the interrelation directly, this method may then be useful to create relatively visible relationships across all lifelines.

2. Interrelation analysis in disaster reporting systems

2.1 Disaster reports

We infer that each lifeline system was considerably damaged as a consequence of the 2011 Tohoku earthquake. In Japan, individual lifeline authorities, local governments, and departmental ministries all published disaster reports due to this earthquake, describing the events in different volumes and various contexts. Here we use the disaster report prepared by a specific joint committee composed of seismology, civil engineering, geological engineering, architecture, mechanical engineering, and urban planning societies [10]. One of the volumes in the report comprises of six chapters (**Table 1**), with one volume focused on lifeline systems (see in **Figure 1**).

This particular chapter is composed of the same material as that of a report prepared by a similar joint committee after the 1995 Kobe earthquake. In Part 3 of this report, some physical damage to roadways, railways, airports, harbors, and other transportation systems was not included, as they formed part of other volumes.

Chapter	Title of chapter	Number of pages	Number of writers
1	Water system	86	20
2	Sewage system	75	10
3	Waste management system	59	14
4	Electric power system	63	6
5	Gas system	22	4
6	Telecommunication system	32	10

Table 1.
Chapters in Part 3 "Damage to Lifeline Facilities and its Restoration" from the "Report on the Great East Japan Earthquake Disaster" [10].

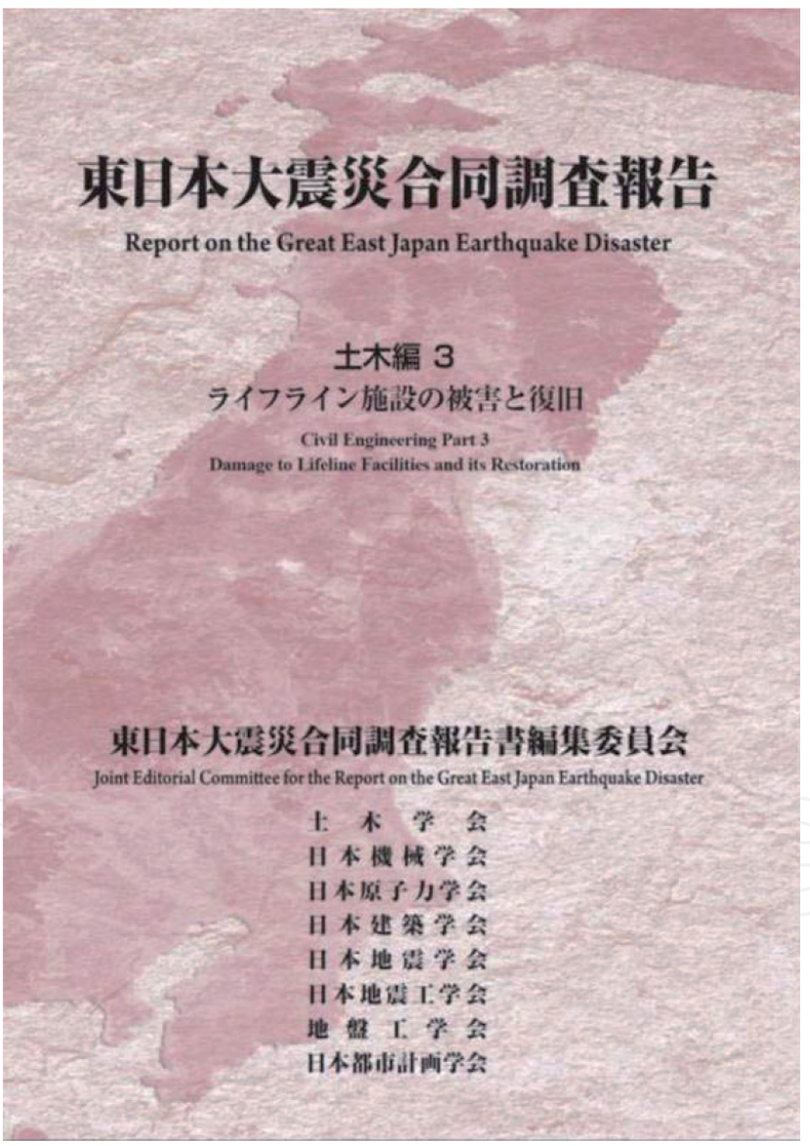


Figure 1.
Capture of the report, titled "Report on the Great East Japan Earthquake Disaster: Volume of Civil Engineering Part 3, Damage to Lifeline Facilities and its Restoration."

The urban gas system was briefly described comparing with other lifeline systems, because a propane gas tank was used in many of the affected areas. The number of affected consumers of gas systems in the Tohoku earthquake was found to be half of those found for the Kobe earthquake.

In Japan, the water, sewage, and waste management systems are all managed by local governments or regional governments, whereas the electric power systems, telecommunication systems, and parts of the gas systems are widely managed through private companies. The report (referred to in **Table 1**) was mainly written by these governments or companies, with the number of writers for chapters on electric power, telecommunications, and gas systems being fewer than those for the chapters of other lifelines. There are 2250 characters per page in the report.

2.2 Hazard classifications

To explain the influence of hazards, such as earthquakes and tsunamis, in the context of this study, "hazard term" was defined as in **Table 2**, and the number of hazard term in Ref. [10] report was detected. Selected terms were basically provided as nouns, with the terms displayed in **Table 2** being English translations. These definitions were used as either single terms or as part of other terms.

These hazard definitions were then classified into four different categories: (1) earthquakes, (2) tsunamis, (3) geo-hazards, and (4) liquefaction. As liquefaction was found particularly remarkable for this earthquake, it was considered within other categories except for geo-hazards. When the term "damage" was used to express geological damage that was not associated to a lifeline facility, the term was omitted from text detection process.

Table 3 lists the number of detected "hazard" definitions used in each chapter of lifeline system. **Figure 2** shows the composition ratio of these terms. The number of hazard terms detected per page was found to be low for the chapter on waste management while exceeding beyond ten words per page for the chapters regarding gas, electric power, and telecommunication systems. The chapter on waste management systems focused on the processing and management methods of waste after the tsunami. The description of the hazard and the extent of damage were also quite brief. Conversely, the chapter on gas systems comprised of the damage analysis caused by seismic ground motion, while the chapter on electric power systems comprised of the damage to the facility as a function of seismic intensity. The frequency of the terms found in the earthquake category also increased for the chapters related to the gas and electric power systems. For the chapters regarding sewage and waste management systems, the terms related to the tsunami were more frequent than those related to the earthquake, where their composition ratios reached approximately 60% or more of the total. While damage to the other lifelines was mainly caused by ground motion, as the waste management plants were all located along the coast, they were unfortunately subjected to flood damage due to the resultant tsunami. For the chapter

Category	Earthquake	Tsunami	Geo-hazard	Liquefaction
Number of words	4	4	3	2
Hazard word	Earthquake Shaking Motion Seismic intensity	Tsunami Inundation Flood Scouring	Subsiding Damage to ground/ground surface Falling out of slope/ embankment/ wall	Liquefaction Sand boiling

Table 2.
A category of hazard term definitions.

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	Water	Sewage	Waste	Electric	Gas	Telecom
Earthquake	256	88	47	404	206	122
Tsunami	208	266	163	256	107	135
Geo-hazard	27	23	6	14	0	7
Liquefaction	78	42	0	63	19	55
Total N_{haz}	569	419	216	737	332	319
N_{haz}/pages	6.6	5.6	3.7	11.7	15.1	10.0

Table 3.
The number of hazard terms detected within the chapters on lifelines.

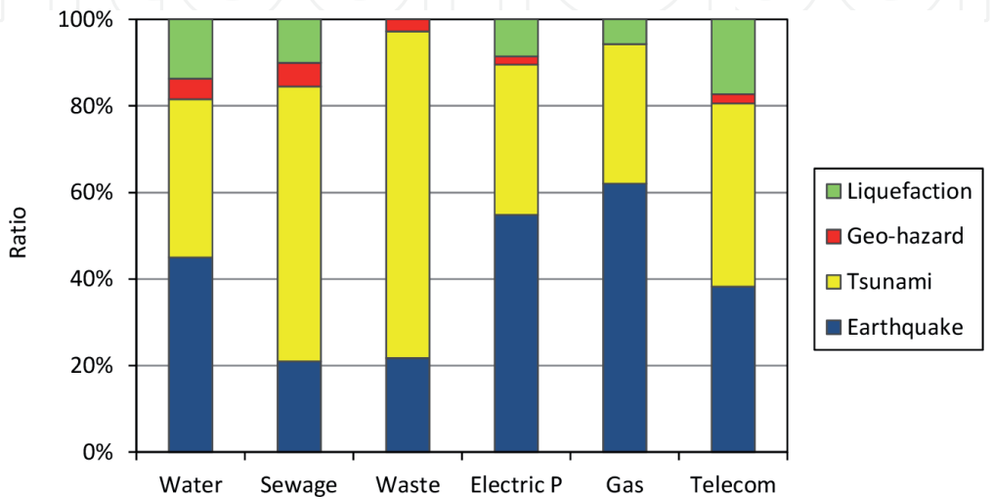


Figure 2.
Composition ratio of key hazard terms detected in chapters related to lifelines.

on waste management systems, many terms related to the processing of tsunami deposits were used. References related to liquefaction were also relatively high.

2.3 Lifeline interrelation analyses based on academic reports

An assessment analyzing lifeline interrelations was conducted using the terms detected from the aforementioned report. First, the lifeline-related terms were identified not only from the lifeline itself but also when the terms were associated with a given lifeline. Second, it was assumed that the use of lifeline-related terms implied that all other lifelines were affected. Last, the number of terms related to the lifelines was counted. The report also described physical damage, suspension, and restoration of lifelines, and not necessarily those of other lifelines.

The lifeline-related terms are divided into sets, as shown in **Tables 4** and **5**. The term related to nuclear power systems was set separately from those related to general electric power, considered the accident at the Fukushima nuclear power plant, which was caused by an earthquake. It is important to examine the lifeline interrelations for the transportation system mentioned in Part 3, regardless of its exclusion in the civil engineering volume. The terms related to the transportation system were added and classified into those associated to roadways and bridges as well as those of traffic functions.

In this case, several lifeline-related terms were set, where terms that were not detected (or only detected two times or less) were omitted in order to accurately identify the number of terms. In addition, when terms were not being used in accordance to the author's intent, its contents were omitted (see notes in **Tables 4** and **5**).

	Water	Sewage	Waste	Electric power	
				General	Nuclear power
Number of terms	8	7	7	11	9
Lifeline-related terms	Water system Water outage Passing water Water supply Water purification Usage restrictions Cooling water Receiving water	Drainage*1 Treatment plant Treatment facility*2 Rain water Sewage Sanitation Sludge	Garbage Waste Debris Human waste Disposal facility Repository site Clean center	Electric power Electricity Power generation Power transmission Power supply Utility pole Power distribution Power outage Resuming Power Power receiving	Nuclear power plant Nuclear power Radioactivity Cesium Radiation Radioactive substance Pollution Precaution district Decontamination

*1: Excludes ground water, *2: Excludes waste water treatment plants

Table 4.
Lifeline-related terms of water, sewage, waste and electric power.

	Gas	Telecom	Transportation	
			Physical	Functional
Number of terms	6	10	9	7
Lifeline-related terms	Gas Leak Fire LNG LPG Incineration	Communication NTT Congestion Mail Wireless LAN Telephone Internet Home page Base station Receiving call/mail	Roadway Bridge National highway Pier Hanging cable*1 Railway Station Airport Harbor	Traffic Transit Vehicle Ship Congestion Gasoline Fuel

*1: Excludes pipes hanging on a bridge

Table 5.
Lifeline-related terms of gas, telecommunication and transportation.

Table 6 shows the number of detected lifeline-related terms in each lifeline chapter. In total, approximately 7518 terms were detected, where about 500 of those were detected in the chapters of the gas and telecommunication systems, smaller number rather than other lifelines: however, no significant difference was found in terms of detected frequency per page.

Figure 3 shows that the ratio of own lifeline-related terms, N_{self}, relative to the detected terms was the same for each lifeline chapter. For example, the ratio indicates the number of water-related terms relative to all other terms in the water systems chapter. The ratio of N_{self} was accounted for approximately 60 to 80%, which describes damage to and the restoration of the lifeline itself. These ratios were neither dependent on the type of lifeline nor the number of writers. Moreover, from the chapter on electric power systems, 10% only of the chapter had described the Fukushima nuclear power plant accident, in addition to radioactivity dispersal.

Subsequently, the terms excluding the own lifeline-related terms from detected terms are summarized in **Figure 4**, which shows the composition ratio of the

	Water	Sewage	Waste	Electric	Gas	Telecom
Total N	2002	1629	2009	900	448	530
N/Pages	23.3	21.7	34.1	14.3	20.4	16.6

Table 6.
The number of detected lifeline-related terms from each lifeline chapter.

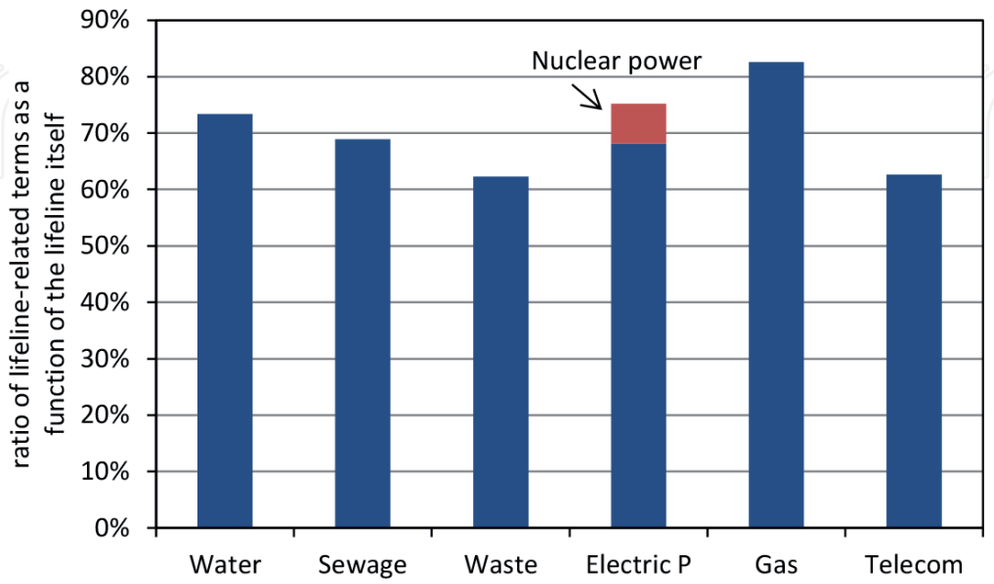
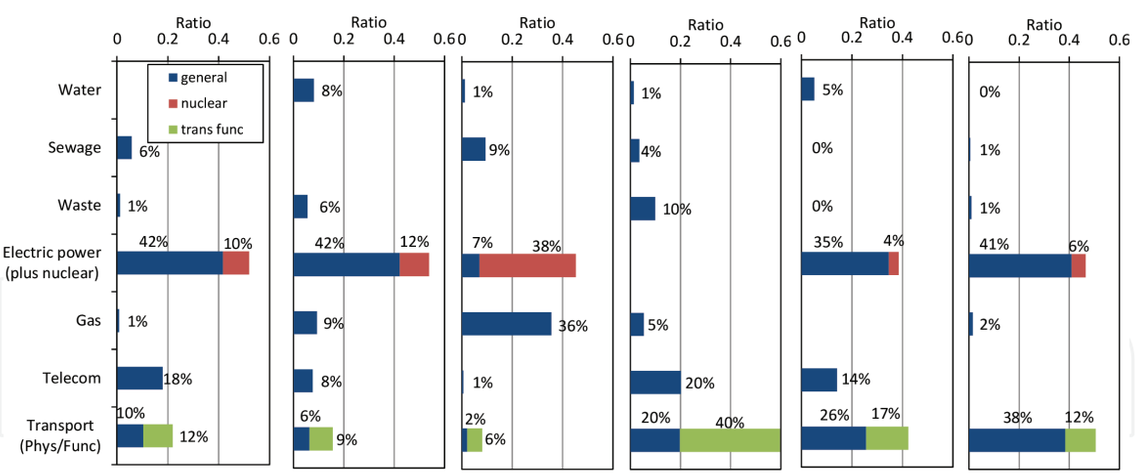


Figure 3.
The ratio of lifeline-related terms as a function of the lifeline itself, N_{self}, within each lifeline chapter.



(a)Water (b) Sewage (c) Waste (d) Electricity (e) Gas (f) Telecom
(N=533) (N=507) (N=757) (N=223) (N=78) (N=198)

Figure 4.
The compositional ratio of lifeline-related terms for all other lifelines.

lifeline-related terms in each chapter. **Figure 4(a)** summarizes the number of detected lifeline-related terms, excluding water-related terms, for the chapter on water systems. The number of terms, excluding those related to the lifeline itself, was found at a minimum (N_{else} = 78) for the gas systems chapter because the chapter was short. The number of terms in all other lifelines ranged from N_{else} = 198 to N_{else} = 757.

The composition ratio for electric power (i.e., general + nuclear power plant) in **Figure 4** shows the ratio of each term related to general electric power and nuclear

power. The ratio of electric power was found to exceed 39% for all lifeline chapters. The most influential lifeline was the electric power system. Here, many terms related to electrical power systems were detected because the electrical equipment in all other lifeline systems were damaged directly by the earthquake and tsunami and operations of other lifeline services were suspended by the power outage.

Terms such as "blackout" (i.e., power outage) and electricity were detected. As a response to the power outage, the terms "power generation," related to an emergency power generator, and "power," in terms of power acquisition and power loss, were also encountered. In this case, the electric power supply had the strongest effect on all other lifelines from the previous studies referenced. Our findings also confirm this. The waste management system, however, was found independent of the electric power system when a nuclear accident was not perceived.

Here, many disaster responses were conducted for the waste management related to the Fukushima nuclear power plant. Within the chapter on waste management systems, no remarkable differences were observed for the nuclear power lifeline-related terms. For the chapters on water and sewage systems, many terms for "radioactive substances" were noticed, with the responses to water purification processing and sludge disposal found to increase due to the accident. It is necessary to study the lifeline interrelation for the case of the other earthquake, which did not result in a nuclear accident, in a similar situation to check the effects in both cases.

The transportation system was also found to have a large influence on all other lifelines. The physical terms "roadway" and "bridge" as well as the functional terms "fuel" and "vehicle" were also detected frequently, regardless of the lifeline system used. For example, the underground pipeline under the roadway along the coast and river was found to be damaged along with the hanging pipeline on the bridge because of the destruction from the earthquake. The electric power, telecommunications, water, and gas systems were all quickly restored, requiring fuel to dispatch the relief goods and personnel to repair the destruction.

Apart from electric power, transportation systems and telecommunication system were then found to be the most common terms. Here, "telecommunication," "telephone," and "wireless" were all extracted several times. While satellite phones were available, telephone services were suspended in a certain area; then, communications among organizations could not be achieved.

3. Lifeline interrelation analyses based on government reports

The degree of influence from lifelines obtained in **Figure 4** shows a different tendency toward disaster scales and the type change. If the same trend was shown for the same earthquake, however, the results of this analyses were found to be valuable. Therefore, similar interrelated tendencies were confirmed in other reports.

In this study, one report (shown in **Table 7**) has used all the other aforementioned reports. These reports (hereinafter referred to as "governmental report") were basically ones in which the jurisdictive ministries and agencies of each lifeline summarized the earthquake/tsunami damage in different types of ways. Therefore, the format of each report differed along with the quantity per page for the academic society report, as mentioned above (herein referred to as the "academic report").

Table 8 shows the counts detected for the lifeline-related terms observed in **Table 4** for the government report. The government reports for sewage and waste were found to have less than the total detectable number compared to that of the academic report. However, the number of all other lifeline-related terms ended up being over 100 words, which was deemed enough to discuss in the composition ratio.

Lifeline	Name of report
Water	The Ministry of Health, Labor and Welfare: *Final report of damage investigation of water supply system during the Great East Japan Earthquake*, 2013
Sewage	The Ministry of Land, Infrastructure and Transport: *Summary of damage to sewage system during the Great East Japan Earthquake*, 2012
Waste	The Ministry of the Environment: *Regional management of disaster waste*, 2014
Power	Tohoku Electric Power Company: *Restoration records of Great East Japan Earthquake,2012* Tokyo Electric Power Company: *Restoration records of electric facility due to Tohoku earthquake*, 2013
Gas	The Ministry of Economy, Trade and Industry: *Report of disaster measure committee of city gas supply based on the Great East Japan Earthquake*, 2012
Telecom	The Ministry of Public Management, Home Affairs, Posts and Telecommunications: *White paper on telecommunic*ations, 2011
Transport	The Ministry of Land, Infrastructure and Transport: *Records of Great East Japan Earthquake*, 2012

Table 7.
A list of governmental reports on the Tohoku earthquake [11–18].

	Water	Sewage	Waste	Electric Tohoku EPCO	Electric TEPCO	Gas	Telecom	Transportation
N	4067	508	782	3398	2790	1441	2621	4955
N_{self}/N	78%	42%	35%	60%	66%	34%	74%	91%
$N-N_{self}$	897	244	569	1027	694	552	687	426

Table 8.
The number of detected lifeline-related terms from governmental reports.

Figures 5 and **6** show the lifeline-related terms (excluding the related terms) in our own lifeline analysis. In regard to electricity, both Tohoku Electric Power Company and the Tokyo Electric Power Company (TEPCO) were shown separately. An analysis of the transportation system was only included in the academic report. In the water supply and sewage report, the lifeline with the highest composition ratio was found to be electricity, with 55% and 54% including nuclear-related terms that were similar to the composition ratio found in the academic report.

According to the waste report, the ratio of gas system was found higher than those quoted in the academic report; however, the composition ratio was monopolized by electric power system and gas system in a similar way. Regarding the report on electric power system, the composition ratio distribution between Tohoku Electric Power and TEPCO was very similar, showing almost 70% for the terms related to the transportation and telecommunication systems.

The transportation system was found to be monopolized in the academic report, but within the governmental report, telecommunication was slightly higher. In the report on gas system, the electric power system and transportation system were much more superior and akin to the academic report where the composition ratios also showed similar values. According to the telecommunication report, the electric power-related term (as with the academic report) was very high at 75%. The fact that the electric power system and transportation system dominated in this report was also similar. For the transportation system, while this was not handled in the academic report, the proportion of electricity was still monopolized at 52%, with sewage, waste, and telecommunications following this.

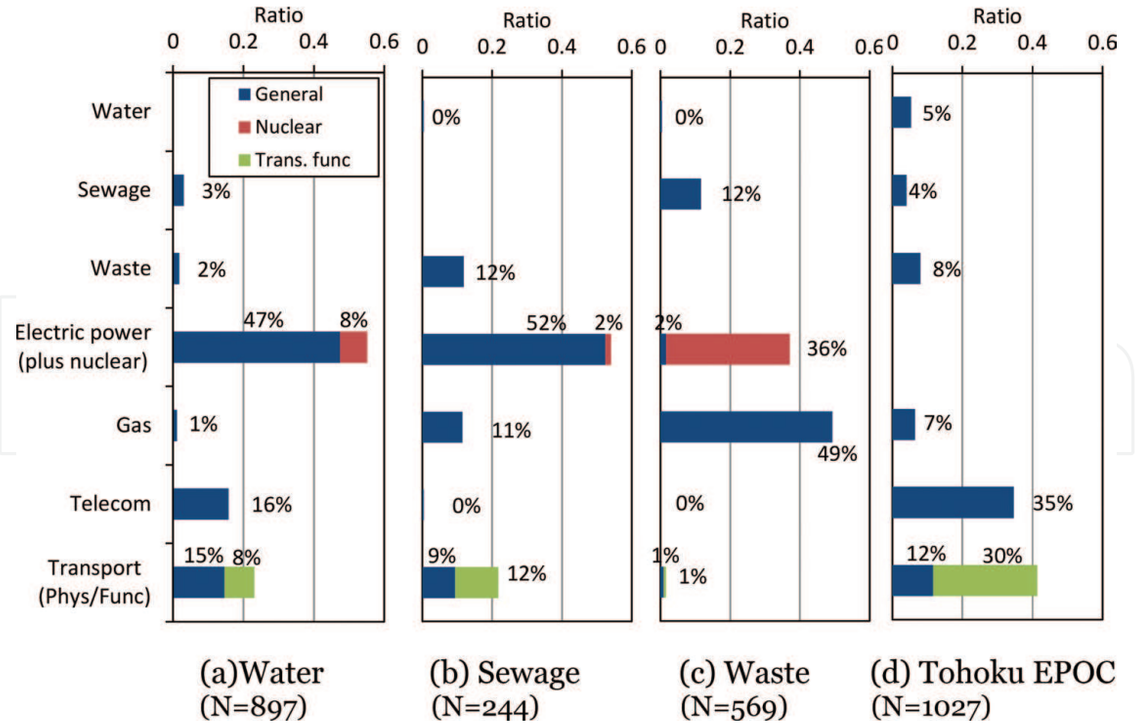


Figure 5.
The composition ratio of lifeline-related terms for all lifelines.

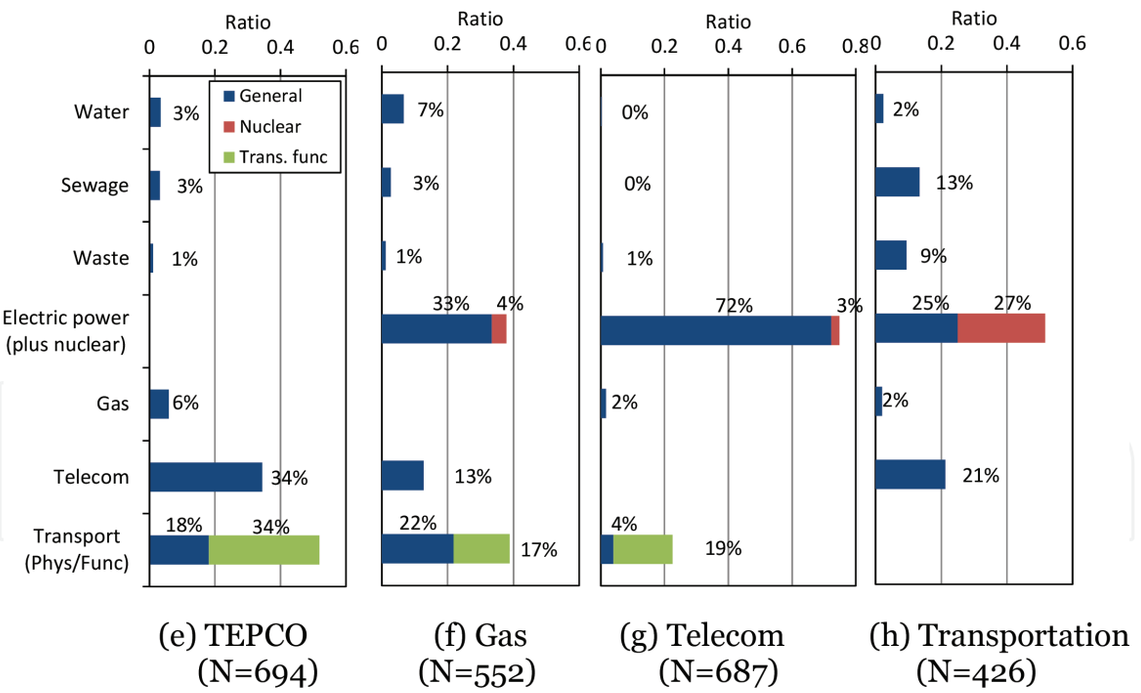


Figure 6.
The composition ratio of lifeline-related terms for all lifelines.

In terms of electricity-related terms in the governmental reports, besides the term "electricity," "blackout," and "power generation" were also used. The latter was perhaps associated with a halt in business operations due to a power outage, where the installation of generators was put into place as a countermeasure. This trend was the same as those for the academic report. In this case, "power supply" was used widely; however, in the governmental report, the term "electric power" was used more than the term "power supply." The composition ratios for power-related terms was found to be similar in both reports, even though the content varied somewhat.

Even if differences were acknowledged for the composition ratio of the related terms between the academic report and the governmental report, this was verified nonetheless by the 5% dangerous rate [19]. Consequently, the premise that a difference in the composition ratio was evident was not readily dismissed for these lifelines (i.e., $8.83 < \chi_{5,\,0.05}^2 = 11.07$ in the water, $6.52 < \chi_{3,\,0.05}^2 = 7.81$ in sewage, and $0.67 < \chi_{2,\,0.05}^2 = 5.99$ in the gas). In other words, the differences were not recognized between repots for these lifeline systems. However, the differences were acknowledged for waste, electric power, and telecommunication systems in the 5% dangerous rate. It has been thought that the reason for these, especially within the governmental reports, was it made it purposefully different from the academic report. These same disasters were understood to have a lifeline where the level of influence between them did not change due to the report issued. Moreover, when the level of influence changed due to the same disaster discussed in the report, it was shown to exert a more dominant lifeline.

4. Discussion

In this study, the evaluation method used for lifeline interrelations was applied to the Tohoku earthquake and quantitatively assessed. This evaluation method was found to quantify the interrelations between all supply systems and transportation lifelines as well. It was found that the influence of the term "electric power" had a large effect and was stated in various reports and academic papers frequently. However, its effect among the lifeline authorities and companies was not shown to be comparable with other lifelines. The value of the composition ratio shown in this study could not be directly used to evaluate a model of lifeline interrelations to predict future lifelines; however, it did become possible to visualize the relationship relatively well across all lifelines.

Lifeline authorities and associated companies have typically provided adequate earthquake countermeasures for their own lifeline facilities; however, a consideration of functions for all other lifelines is usually not sufficient. Based on the results of this study, it was expressly understood that the interrelations for earthquakes with all other lifelines apart from electric power were motivated to prepare backup facilities. Conversely, in an academic sense, modeling the mutual influence among a few lifelines as well as parts of a lifeline resulted in new interrelations that were sometimes overlooked. Indeed, this result can only be inferred as basic material for the modeling of interrelated structures, as we do not consider the physical or functional structures. For future studies, various viewpoints would then be necessary to analyze this perspective in more detail.

Although this study focused on the Tohoku earthquake, comparing the results with other reports such as flood disasters could also be a future task. Since these issues are likely to be affected by the differences in the hazards, as well as the degree of damage to the lifeline (as mentioned previously), consideration should still be given.

5. Conclusions

In this study, lifeline-related terms in disaster reports were detected and quantitatively evaluated to observe the relationships among lifelines during the 2011 Tohoku earthquake disaster. The study can be summarized as follows:

- The composition ratio of each term related to electric power exceeded 39% for all lifelines. This shows that the electric power system was the most influential of all other lifelines.

- A small influence from nuclear power plant accidents was mentioned for all lifelines. This influence was the highest for the waste management system. The effect of water and sewage systems was also high, with many references to radioactive substances found within each chapter.

- An influence on the transportation system for all other lifelines was the strongest after the electric power system. As the earthquake-affected areas were found to be vast, restoration was a timely process. The disaster assistance from all other areas was also influenced.

- With regard to water supply, sewage, and gas, no difference in composition ratio for lifeline-related terms were found, regardless of the type of report for the same disaster. Conversely, in the case of electric power, telecommunications, and waste, while the composition ratio varied depending on the report, it was shown that the dominant lifelines were similar.

- The result of this study could be used as basic data for modeling the interrelated structures. However, since it cannot be guaranteed that similar results will be obtained for any of the disasters mentioned, it will be necessary to verify the reproducibility of this method by applying it to other disasters.

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