HEALTHCARE SYSTEM RESILIENCE AFTER THE 27F EARTHQUAKE AND TSUNAMI

M. Monsalve[1] & J.C de la Llera[2]

[1] Pontificia Universidad Catolica de Chile and Research Center for Integrated Disaster Risk Management (CIGIDEN) ANID/FONDAP/1522A0005, Santiago, Chile, mauricio.monsalve@cigiden.cl

[2] Pontificia Universidad Catolica de Chile and Research Center for Integrated Disaster Risk Management (CIGIDEN) ANID/FONDAP/1523A0009, Santiago, Chile

Abstract: *Severe earthquakes often cause considerable physical harm to the communities affected by them. Hence, a robust and functional healthcare system is essential to ensure the survival and recovery of the injured. However, even if the hospitals and other healthcare centers are able to withstand adequately an earthquake, their functionality may still be affected if the lifelines and critical infrastructure they depend on have been disrupted. These disruptions may affect the delivery of healthcare in various ways, for example, damaged roads impede or difficult the arrival of the injured to healthcare centers, electricity blackouts forces hospitals to use gas generators for a limited-time autonomy, etcetera. This work reviews the situation of the healthcare system of the Greater Concepción conurbation in Chile after the Mw 8.8, 27 February 2010 earthquake and tsunami, where the disruption of essential lifeline services resulted in the loss of functionality of healthcare centers. Available data describes which healthcare centers were affected by the earthquake and tsunami, when the lifeline services were restored and when these healthcare centers resumed operation. This valuable information is used to construct macro-models that combine the recovery of lifelines and the healthcare system after severe earthquakes, and demonstrates the importance of interdependencies and healthcare systems.*

1 Introduction

Severe earthquakes often cause considerable physical harm to the communities affected by them. Hence, a robust and functional healthcare system is essential to ensure the survival and recovery of the injured.

However, even if the hospitals and other healthcare centers are physically able to withstand adequately an earthquake, their functionality may still be affected if the lifelines and critical infrastructure they depend on have been disrupted. These disruptions may affect the delivery of healthcare in various ways, for example, damaged roads impede or difficult the arrival of the injured to healthcare centers, electricity blackouts forces hospitals to use gas generators and the “countdown” of autonomy associated with this, etcetera.

This work reviews the situation of the healthcare system of the Greater Concepción conurbation in Chile after the Mw 8.8, 27 February 2010 earthquake and tsunami. The conurbation comprises several communes (municipalities), namely Concepción, Coronel, Chiguayante, Florida, Hualpén, Hualqui, Lota, Penco, San Pedro de la Paz, Talcahuano and Tomé. The commune of Concepción is the most important in terms of public administration, services and businesses. The commune of Talcahuano, however, is the most important economically, since it is one of the largest and most active ports in Chile. The other communes are mostly residential.

The Greater Concepción conurbation suffered extensive damage from the earthquake and tsunami. Besides the damage to residential buildings, the disruption of essential lifeline services resulted in the loss of functionality of healthcare centers. Available data describes which healthcare centers were affected by the earthquake and tsunami, when the lifeline services were restored and when these healthcare centers resumed operation.

This valuable information is used to construct macro-models that combine the recovery of lifelines and the healthcare system after severe earthquakes, and demonstrates the importance of interdependencies and healthcare systems.

2 Overview of the performance of the Greater Concepción

The Mw 8.8 February 27th, 2010, Chile earthquake, which occurred at 6:34 UTC (3:34 local time), struck Central Chile, from latitudes -33 to -38, affecting 12 million people and 4 million households, and causing USD 30 billions in direct and indirect losses (de la Llera 2017; Pan American Health Organization 2010).

The Greater Concepción conurbation was severely affected by the earthquake and tsunami, because of its closeness to the earthquake source. Several buildings experienced severe damage (57) and one collapsed (Leyton et al 2011). The tsunami wave entered 0.5 km into Talcahuano, leaving extensive damage to the port infrastructure and carrying vessels inland (Elnashai et al 2010). The other ports of the conurbation, Lota and Coronel, also suffered damage, but mostly due to the ground motion. Businesses were heavily impacted, with most being close for months after the event (Alonso-Dos-Santos & Llanos-Contreras 2019; Elnashai et al 2010).

When the earthquake struck, several services ceased to function or had to function partially. Lifelines were disrupted: there were widespread blackouts due to damage in electric distribution poles and transformers, drinking water pipelines had been damaged in various points, roads were filled with debris and some bridges were damaged. In particular, the collapse of the main bridge that crossed the Biobío river, which separates the Greater Concepción into two, augmented the crossing time from minutes to 1-2 hours (Elnashai 2010).

Fig. 1 shows the restoration of service of different utilities, namely, electricity, mobile telephony, landline telephony and drinking water in the Biobío region and in the Talcahuano and Concepción communes (Dueñas-Osorio & Kwasinski 2012). At two weeks after the event, electricity and telephony coverage was above 95%, while tap water coverage was approximately 10% in Talcahuano and 75% in Concepción.

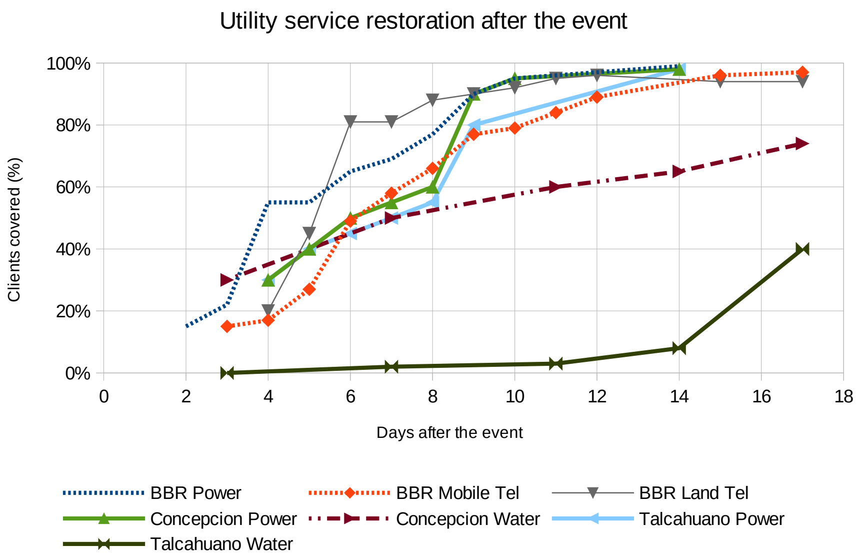

Figure 1. Utility coverage during the days following the earthquake. Terms: BBR stands for Biobío region, Mobile Tel stands for mobile telephony, Land Tel stands for landline telephony.

3 Performance of healthcare centers

Several healthcare centers suffered physical damage and their quality of service suffered because of the disruption in utilities and the increased arrival of people injured due to the earthquake.

This work considers the following six healthcare centers that were affected by the earthquake:

- Hospital Regional Guillermo Grant Benavente, located in Concepción, which is the main public hospital of the region;
- Hospital clínico IST, located in Talcahuano, which belongs to a work safety mutuality;
- Hospital Las Higueras, located in Talcahuano, which is a public hospital;
- CESFAM Juan Soto Fernández, located in Concepción, which is a public family hospital;
- CESFAM Santa Sabina, located in Concepción, which is a public family hospital;
- CESFAM Alcalde Leocán Portus, located in Talcahuano, which is also a public family hospital.

To be noted, CESFAMs are lower complexity hospitals, which outside office hours work as emergency hospitals. If the patients have more challenging conditions, they are transferred to higher complexity public hospitals. Hospital Regional and Hospital Las Higueras are high complexity public hospital, hence they have the capacity to provide care to the most critical patients. Hospital clínico IST is mostly concerned with occupational medicine and does not belong to the public healthcare system.

The location of the healthcare centers mentioned above is shown in Fig. 2.

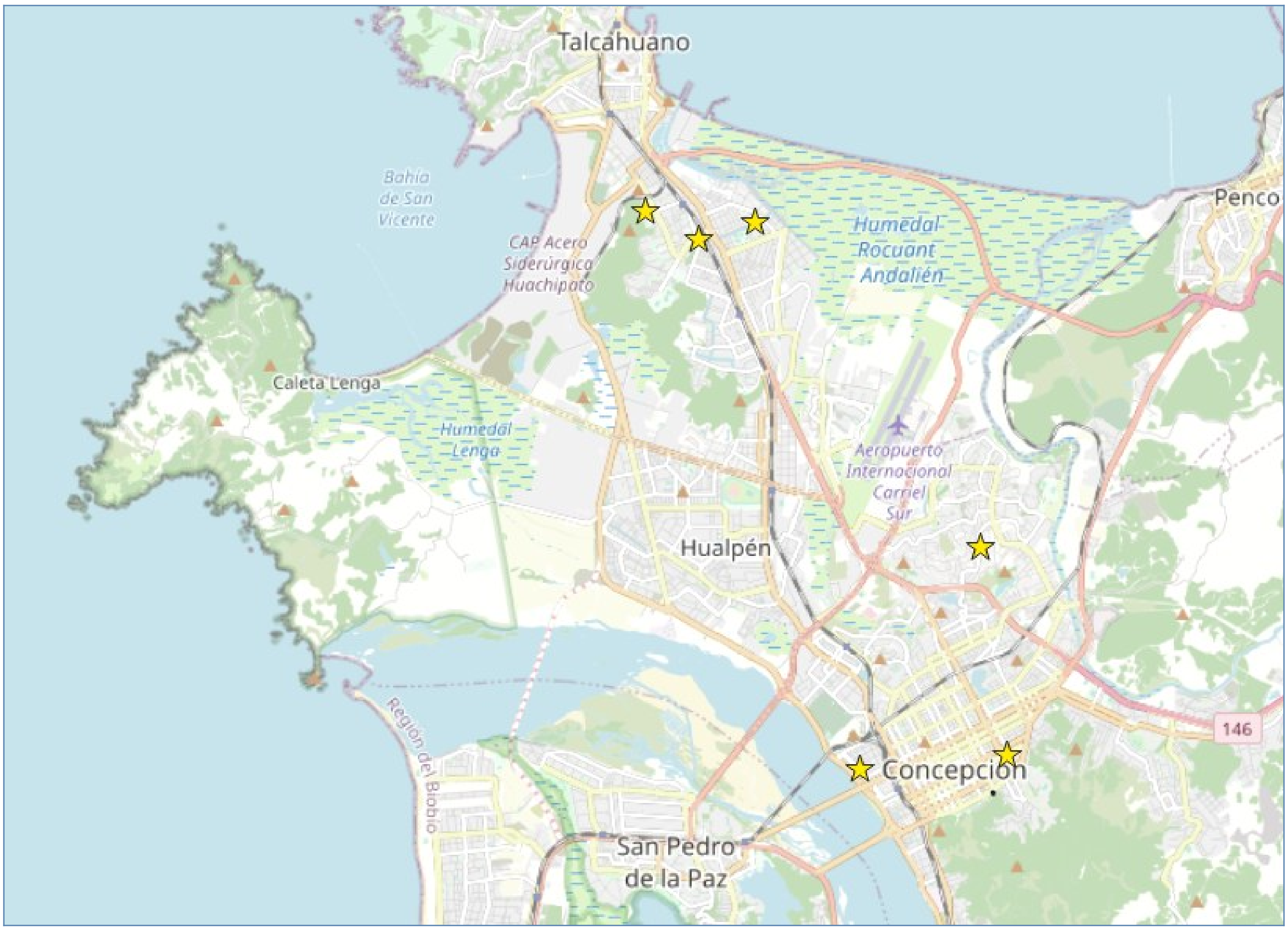

Figure 2. Health-care centers considered in this work.

The sample of healthcare centers was chosen due to their importance. The conurbation did not have many more centers of their scale. In addition, smaller private clinics were not taken into account because of their smaller impact in terms of patient care. Pharmacy stores were also excluded from this analysis.

4 Dependence on utilities and recovery

Regarding the access to essential utilities, electricity was the service that recovered first. Most healthcare centers had access to power grid electricity within a week of the event and all of them within three weeks. This was followed by landline telephony and internet, which took four weeks to recover completely for all centers. Finally, the access to tap water was the last to recover. While half of the healthcare centers had access to tap water within 10 days, it took seven weeks for all of them to have access to it. The time series of the number of healthcare centers without access to services, for each of the described services, is shown in Fig. 3.

As Fig. 3 shows, all of the healthcare centers considered experienced loss of service from the three lifelines considered. This meant that these centers had to operate with limited capacity. However, some of them could function with limited autonomy for a brief period of time: three of the had backup water systems while four of them had power backup.

The daily number of healthcare centers that experienced at least the shortage of one of the essential utilities is shown in Fig. 4.

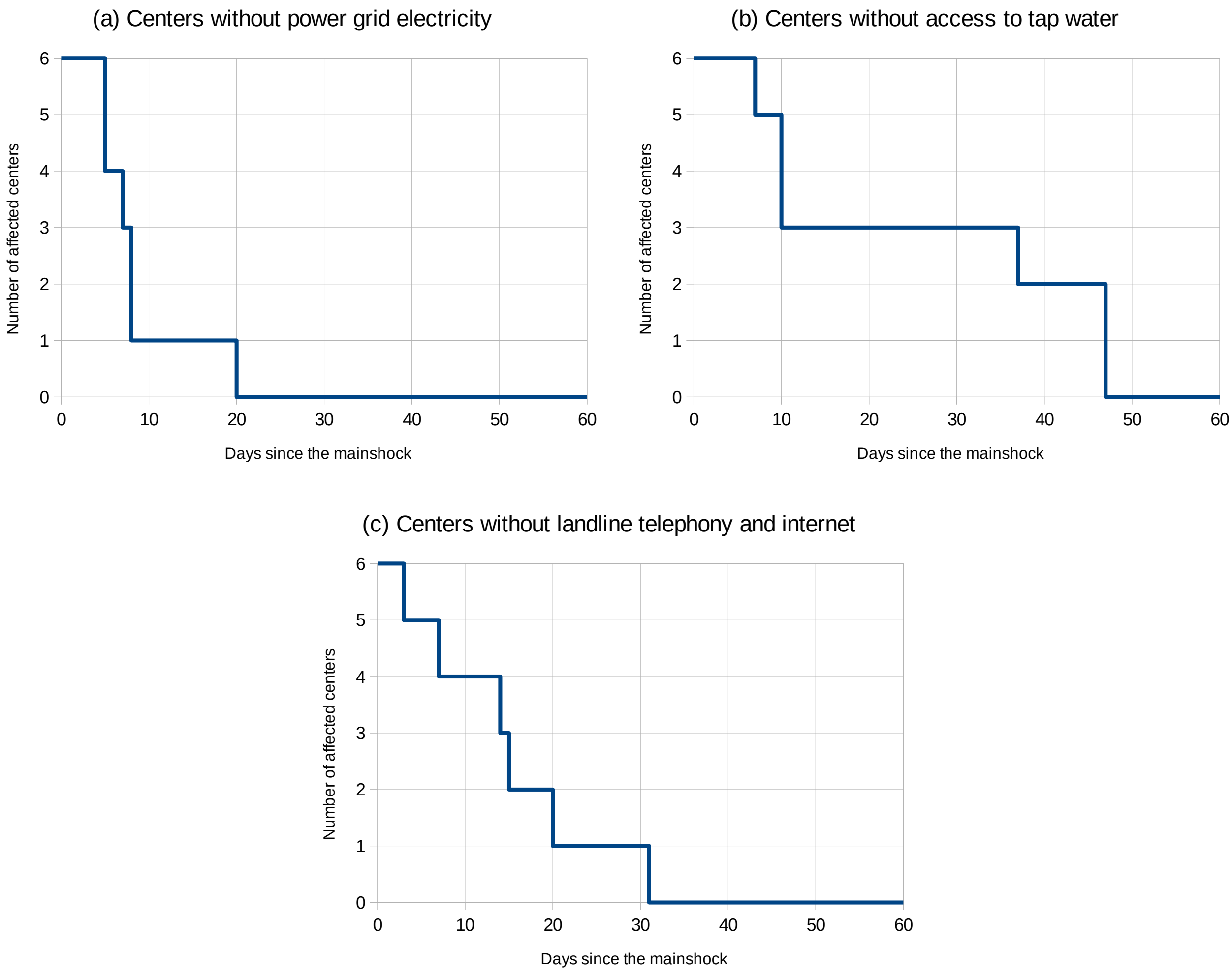

Figure 3. Number of healthcare centers affected by the lack of availability of essential utilities: (a) power grid, (b) tap water, (c) landline telephony and internet. All charts depict daily time series.

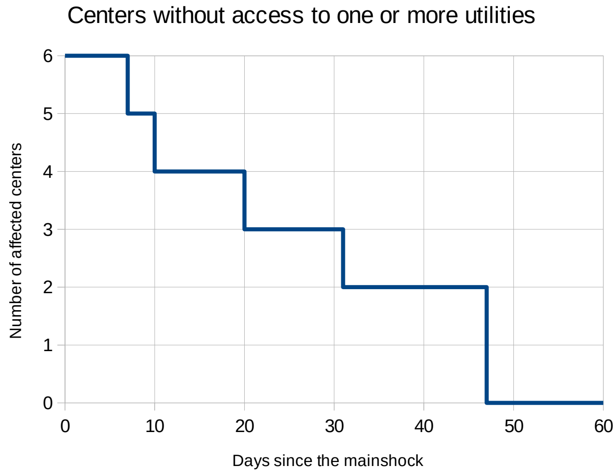

Figure 4. Number of healthcare centers without access to at least one utility.

5 Reproducing the curve using area statistics

The availability of time series of utility coverage in the Greater Concepción conurbation (see Fig. 1) presents itself as an opportunity to attempt to infer or reproduce the number of affected healthcare centers (see Fig. 4) using "mixing" assumptions.

Given that a normal condition in an structurally safe healthcare center requires coverage from utilities, it can be stated that center *X* will function normally if

$$f(X,t)=w(X,t)\wedge e(X,t)\wedge i(X,t), \tag{1}$$

where

- *w*(*X*, *t*) yields True if and only if *X* has tap water service on day *t*,
- *e*(*X*, *t*) yields True if and only if *X* has electricity from the power grid on day *t*,
- *i*(*X*, *t*) yields True if and only if X has landline internet and telephony on day *t*, and
- *f*(*X*, *t*) yields True if and only if X access to utilities has been normalized.

Conversely, Eq. 1 can be translated into a formula for inferring that healthcare center *X* is not yet normalized; it suffices to apply the negation (not, ¬) operation.

Eq. 1 can serve as a guideline to define a function to estimate the number of healthcare centers in a given area (in this case, the six centers considered from the Greater Concepción area). However, this requires turning the logical formula expressed in Eq. 1 into a continuous formula, which, to begin with, can be done in a number of ways.

Since the proportion of covered clients for each utility is known (Fig. 1), the following are considered known:

- $w(t)\in[0,1]$ is the proportion of clients with tap water service in the area,
- $e(t)\in[0,1]$ is the proportion of clients with electricity in the area, and
- $i(t)\in[0,1]$ is the proportion of clients with landline internet and telephony.

The objetive is to use $w(t), e(t)$ and $i(t)$ to estimate the number of disrupted healthcare centers.

Three strategies are followed to accomplish this objetive. The first strategy follows a "homogeneous mixing" approach. In this strategy, $w(t), e(t)$ and $i(t)$ are treated as independent probabilities. Hence, the probability (proportion) of healthcare centers being disrupted is

$$f_{\text{hom}}(t)=1-\Pr(\text{has full coverage}) \tag{2}$$

which can be rewritten as

$$\Rightarrow f_{hom}(t) = 1 - w(t)e(t)i(t). \quad (3)$$

Eq. 3 may be unrealistic, for it is reasonable to expect some degree of correlation between the zones in which services are unavailable.

The second strategy assumes perfect overlapping between the areas that are not serviced. This assumption is overly optimistic, for it only focuses on the worst performing lifeline. For example, if 10% of the centers do not have landlines, 15% do not have water and 20% do not have electricity, it will be assumed that the 10% without landlines and the 15% without water are already included in the set of 20% without electricity. Following this idea, the optimistic estimate can be written as

$$f_{opt}(t) = \max\{1 - w(t), 1 - e(t), 1 - i(t)\}. \quad (4)$$

The third strategy assumes that areas not serviced by different services are disjoint or, equivalently, that a client may experience service disruption from at most one utility. For example, if 10% of the centers do not have landlines, 15% do not have water and 20% do not have electricity, it will be assumed that 45% of the clients are experiencing service disruption. Following this idea, the pessimistic estimate is

$$f_{pes}(t) = \min\{1, 3 - w(t) - e(t) - i(t)\}. \quad (5)$$

Note that Eq. 5 ensures that f_{pes} is not greater than 1.

6 Estimation results

The three quantities previously defined, i.e., Eqs. 3-5, were applied to the service restoration curves previously shown in Fig. 1. The formulas were applied separately to the Concepción curves (Concepción Power, Concepción Water, BBR Land Tel) and Talcahuano curves (Talcahuano Power, Talcahuano Water, BBR Land Tel). Then, the estimates were added and multiplied by three in order to estimate the situation of the six healthcare centers considered in this work (three in Concepción and three in Talcahuano).

Fig. 5 shows the results of the estimates against the actual data, which was previously depicted in Fig. 4. Since the data in Fig. 1 merely spans 15 days, it is not possible to generate a 60-day long curve. However, as it can be observed, there is good agreement for the days where there is available data. It can also be observed that the homogeneous and pessimistic estimates seem overall more accurate than the optimistic estimate. However, proper verification of this may require collecting further data from this and additional case studies.

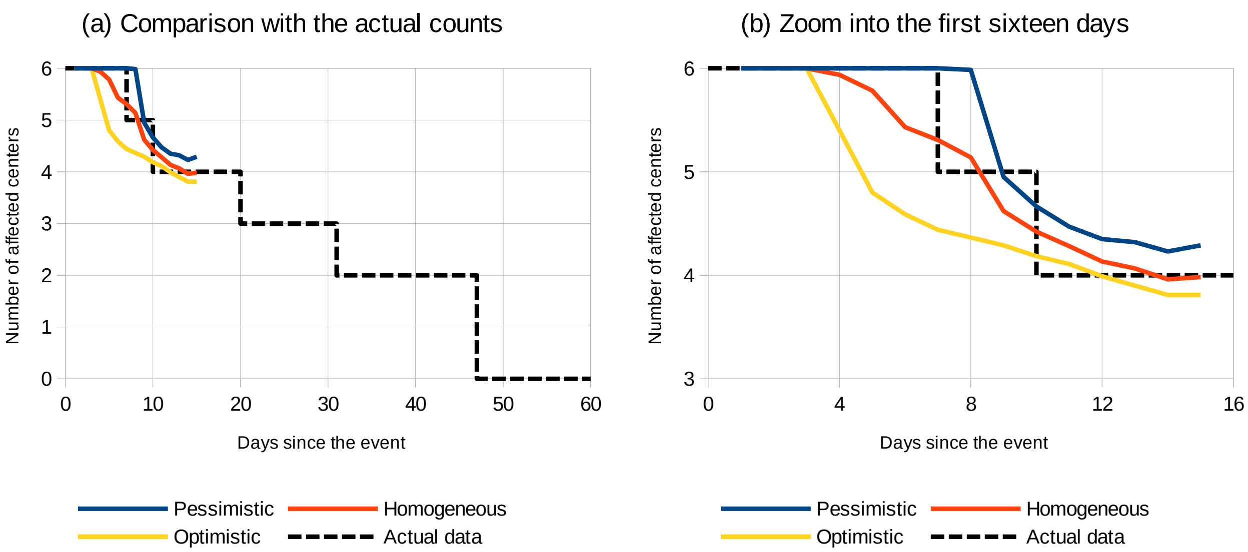

Figure 5. Estimated and actual number of healthcare centers without access to at least one utility. Insets: (a) visualization against 60 days of data and (b) zoom into the first 16 days.

Despite the use of limited data and a limited case study, these results form a first step into modeling the functionality of healthcare systems using their dependence on other lifelines and considering area-wide statistics, e.g., proportion of serviced or unserviced clients. Such statistics represent systems in a coarse manner, but may be less difficult to obtain that micro-level data of serviced clients. In fact, such data can be collected from newspapers or press releases by utility companies.

In addition to the above, it may be possible to make use of models that predict the macro-level dynamics of interdependent restoration systems (Monsalve & de la Llera 2019; Johnson & Mieler 2022; Kammouh et al 2018). For example, a statistical model may be inferred from Fig. 1 and may be used to predict scenarios of join recovery of interdependent utilities. Using these, the exercise shown in Fig. 5 may be repeated, but with stochastically generated recovery scenarios. This might help foresee the likelihood of undesirable situations in which healthcare centers take considerable time to return to complete functionality.

7 Conclusions

The operational continuity of healthcare centers is essential in a adequately functioning society, yet this importance is heightened in the event a catastrophic situation occurs, such as a high intensity earthquake. Immediate medical attention may help prevent the loss of life and further suffering of the injured. However, to function properly, healthcare centers need the continuous provision of essential utilities, such as tap water, electricity and telecommunications. Without these, they need to resort to backup systems, which provide a limited-time autonomy.

This work studied the performance of the lifelines and healthcare system of the Greater Concepción conurbation after the Mw 8.8 February 27 Chile earthquake. It compiled and showed data from the service restoration for several utilities and six important healthcare centers from the area. By noting how the functionality of healthcare centers depends on these utilities, simple time series models were devised to estimate (or give bounds) the restoration of healthcare centers over time. The results showed agreement between the actual counts of disrupted healthcare centers over time and the estimates, which were constructed purely using utility coverage data.

8 Acknowledgements

This work has been sponsored by the Chilean government through the Research Center for Integrated Disaster Risk Management (CIGIDEN), ANID/FONDAP/1523A0009, and the research project Multiscale earthquake risk mitigation of healthcare networks using seismic isolation, ANID/FONDECYT/1220292.

9 References

Alonso-Dos-Santos M., Llanos-Contreras O. (2019). Family business performance in a post-disaster scenario: The influence of socioemotional wealth importance and entrepreneurial orientation. *Journal of Business Research*, 101:492-8.

de la Llera J.C., Rivera F., Mitrani-Reiser J., Jünemann R., Fortuño C., Ríos M., Hube M., Santa María H., Cienfuegos R. (2017). Data collection after the 2010 Maule earthquake in Chile. *Bulletin of Earthquake Engineering*, 15:555-88.

Dueñas-Osorio L., Kwasinski A. (2012). Quantification of lifeline system interdependencies after the 27 February 2010 Mw 8.8 offshore Maule, Chile, earthquake. *Earthquake Spectra*, 28(1_suppl1):581-603.

Elnashai A.S., Gencturk B., Kwon O.S., Al-Qadi I.L., Hashash Y., Roesler J.R., Kim S.J., Jeong S.H., Dukes J., Valdivia A. (2010). The Maule (Chile) earthquake of February 27, 2010: Consequence assessment and case studies. *MAE Center Report*, 10-04.

Johnson L.A., Mieler D.H. (2022). Assessing Lifeline Interdependencies and Restoration Performance in San Francisco Using Qualitative Methods. *Lifelines* (pp. 782-796).

Kammouh O., Cimellaro G.P., Mahin S.A. (2018). Downtime estimation and analysis of lifelines after an earthquake. *Engineering Structures*, 173:393-403.

Leyton, F., Montalva, G. y Ramírez, P. (2012). A preliminary study of seismic microzonation of Concepción based on microtremors, geology and damages patterns. *Obras y Proyectos*, 11:40-46.

Monsalve M., de la Llera J.C. (2019). Data-driven estimation of interdependencies and restoration of infrastructure systems. *Reliability Engineering & System Safety,* 181:167-80.

Pan American Health Organization (2010). *El Terremoto y Tsunami del 27 de Febrero en Chile: Crónica y lecciones aprendidas en el sector salud*. Santiago, Chile.