Estimating the impact of earthquake-induced power outages on different economic sectors in Chile

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The damage induced by strong earthquakes on the components of Electric Power Networks (EPNs) can seriously compromise the ability of these systems to generate and distribute electric power to final users and to interconnected utilities and industries. This results in large-scale impacts across infrastructure systems and economic sectors that rely upon EPNs. The objective of this work is to estimate the economic losses due to the reduction of the Chilean EPN functionality after the occurrence of disruptive seismic events. Economic losses have been estimated, at country and regional level, by applying the following main steps: (1) estimation of ground motion intensity measures for three earthquakes at the location of the EPN system components; (2) evaluation of the physical damage on the EPN system components; (3) evaluation of the EPN system functional consequence; and (4) estimation of the economic impacts on the electricity sectors and on the interconnected economic activities at regional and national level. Results of this analysis allow identifying the most impacted regions on the basis of the most impacted economic activities and can support decision-making for future investments to reduce the economic impacts produced by disruptive seismic events on EPNs and their interdependent industries.

Keywords: electric power networks, economic losses, input-output model, seismic hazard, interdependencies.

1. Introduction

Electric power networks (EPNs) are key infrastructures that sustain the welfare, safety, and economy of a country and, thus, their continuous operation is fundamental. However, natural and anthropogenic hazards, as well as random failures, can damage EPN components and seriously compromise the electric supply to residential, commercial and industrial consumers. The inability of an EPN to meet the demand of electricity may cause vast societal impacts that go beyond direct consequences of service interruption to individual EPN customers. Because EPNs are extensively interconnected to several other critical infrastructures, such as other utilities and industrial consumers, society at large may be strongly affected by electric supply interruption (Li et al. 2018).

In the case of Chile, EPNs are strongly exposed to natural hazards, especially earthquakes, that may cause large scale affectation; for example, the estimated average annual loss due to earthquakes in Chile has been estimated at around

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1.2% of its Gross Domestic Product (GDP) (UNISDR, 2015). It is thus relevant to estimate the impact that strong ground motions generate on the EPN system by quantifying the economic losses caused by such interruptions in the EPN itself and the other utilities and industries that rely upon the EPN.

Economic quantification of service disruptions in interdependent systems has been addressed by macroeconomic models, such as Input-Output (IO) model, Computable General Equilibrium (CGE), and Social Accounting Matrix (SAM) (Okuyama and Santos, 2014; Koks et al., 2016). The first two approaches are the most commonly used in disaster impact analysis and several extensions based on the IO model have been developed, such as the Inoperability Input-Output model (IIM) (Haimes and Jiang, 2001), the multiregional IO modeling (Pant et al. 2011), and the combination of linear programming with IO modeling (Rose et al. 1997; Koks and Thiessen, 2016; He et al., 2019).

The IO model is able to represent the economic transactions between the different economic activities that comprise the productive structure of an economy (Miller & Blair, 2009). It presents several limitations due to its linearity, its rigid structure, and its inability to account for resource constraints and the responses to price changes (Rose, 2004; Okuyama and Santos, 2014; Koks et al 2016). However, it has been adopted in this work because it is simple and it is considered to perform well for assessing the impact produced by a natural disaster (Okuyama and Santos, 2014).

The present analysis estimates the economic impacts induced by the loss of functionality experienced by the Chilean electric power transmission network due to the structural damage produced by the occurrence of earthquakes. Power generation units and substations are the main EPN components considered in this work.

2. Study aim and framework of analysis

This study is a first attempt at understanding the mediating role of the EPN on the economy of Chile at national and regional scale, when the EPN is affected by the occurrence of strong earthquakes. Because most of the territory of Chile is connected by one large EPN and the regional economies are also interdependent on each other, it is not obvious how the ubiquity of the damage to the EPN will economically affect the regions. Thus, three earthquake events with the same moment magnitude but with different epicentral locations have been selected to analyze the impact of earthquake-induced power outages on different Chilean economic sectors.

To estimate the economic impacts due to the EPN disruption after an earthquake, the following steps are carried out: (i) sampling of consistent ground motion intensity measures at the EPN component sites, with respect to a given earthquake epicenter and magnitude; (ii) evaluation of the physical damage on the different EPN components by using seismic fragility functions; (iii) evaluation of the EPN performance, in terms of unsupplied energy at national and regional level, using a power flow optimization model; and (iv) estimation of the economic affectation at national and regional level, using the productive relations between industries and consumers through the IO model. All of these analyses have been carried for the first hour after the earthquake.

Steps (i)-(iii) are repeated a very high number of times for each of the three selected earthquake events in order to consider different sources of uncertainty in the evaluation. Note that this procedure is a version of the Seismic Probabilistic Risk Assessment (SPRA) framework used in some previous studies (e.g., Jayaram and Baker, 2010; Poulos et al., 2017) tailored to the research question considered in this work. In SPRA, however, step (i) would include the random generation of earthquake events (location and magnitude) according to seismicity recurrence relations, while steps (iii) and (iv) would be combined into a general "system performance evaluation" step.

3. Evaluation of the Electric Power Network performance after an earthquake

3.1. Ground motion intensity generation

The ground motion intensity at the site of each EPN system component of interest (i.e., power generation units and substations) is characterized here by the peak ground acceleration (PGA). Given an earthquake event, defined by an epicenter and a magnitude, earthquake ground motion intensities are obtained using a proper ground motion prediction models (GMPMs) for the geographical area of interest, as has been done by several previous works (e.g., Jayaram and Baker, 2010; Poulos et al., 2017). Specifically, the GMPM developed by Abrahamson et al. (2016) for subduction earthquakes is used here. The PGA values are sampled using:

$$\ln \boldsymbol{IM} = \ln \overline{\boldsymbol{IM}} + \boldsymbol{\sigma} \circ \boldsymbol{\varepsilon} + \tau\eta \qquad (1)$$

where $\overline{\boldsymbol{IM}}$ is the vector of median PGAs at all sites, which is given by the GMPM and depends on earthquake magnitude, the distances from each site to the earthquake rupture surface, and local soil conditions characterized by the average shear wave velocity in the top 30 m of soil (Vs30); $\boldsymbol{\sigma}$ is the vector of intra-event standard deviation term for all sites, given by the GMPM; τ is the inter-event standard deviation term from the GMPM; $\circ$

denotes the entrywise product of vectors; η is a standard normal random variable; and $\boldsymbol{\varepsilon}$ is a multivariate normal random variable with zero mean and unitary standard deviation and a covariance matrix constructed using the spatial correlation model developed by Goda & Atkinson (2010).

3.2. Estimation of the damage state of EPN components

Seismic fragility curves represent the conditional probability of failure of a component given a ground-motion intensity level and they are here adopted to sample the (physical/structural) damage state of each system component (EPRI, 2013). Several fragility curves for power generation units and substations, representing different structural damage levels, e.g., from minor to complete damage, can be found in the literature (e.g., FEMA, 2003). In this work, a binary state model for the structural damage state of each component is adopted by considering the highest fragility curve given in FEMA (2003), i.e., the one corresponding to the minor component damage state, in a conservative manner. Transmission lines are assumed to be disconnected from the network when one of the components they connect fails.

3.3. Post-earthquake EPN performance

System performance depends on the functionality of system components. Given the binary state model adopted for the component physical damage (see Section 3.2), it is straightforward to assume a binary state model for the component functionality, i.e., a component stops to function if it has structural damage. Once the functionality of each component is determined, it is possible to evaluate the system performance by simulation. In particular, the Direct Current – Optimal Power Flow (DC-OPF) model is adopted to estimate the EPN performance in terms of unsupplied energy for the first hour after the earthquake occurrence. The objective function of the optimization problem is to minimize the sum of the total generation cost and the total unsupplied energy; to penalize the occurrence of unsupplied energy, very large service interruption costs are assumed. Details of the optimization problem formulation are not reported here for brevity; the interested reader is referred to Ferrario et al. (2019).

Once the unsupplied energy at national and regional levels is computed, the electricity outage ratio, at national, α, and regional levels, α^{reg}, is obtained as the ratio between the unsupplied energy and the demand of energy at the appropriate geographical scale.

For each earthquake event, M simulations are performed by sampling M ground motion intensity maps (Section 3.1) and, consequently, M system damage configurations (Section 3.2). Then, M evaluations of the system performance can be carried out and the expected outage ratio of electricity can be estimated, at national, $\bar{\alpha}$, and regional, $\bar{\alpha}^{reg}$, levels, by averaging the M electricity outage ratios at the geographical scale of interest.

4. Estimation of the economic impacts associated with the EPN disruption

4.1. Basics of IO analysis

This work follows the approach of Rose et al. (1997) to estimate the economic impact, as missed production and unmet consumption, of a decrease in electricity supply to a region. This is done by using IO models, which represent the economic structure of a geopolitical unit (e.g. a country) as a collection of N economic activities that interact with each other through economic transactions (Rose & Miernyk, 1989). These interactions are represented by the IO matrix $\boldsymbol{A}$ of dimension $[N \times N]$, whose (i,j)-element (or simply $A_{i,j}$) represents a coefficient of the production and varies between 0 and 1; more in details it indicates how much of the costs of activity j are explained by sales of activity i to activity j, i.e., how much activity i sells to activity j when activity i buy one dollar.

Then, matrix $\boldsymbol{A}$ permits relating the total production $\boldsymbol{p}$ and the final consumption (non-intermediate demand) $\boldsymbol{c}$ as follows:

$$\boldsymbol{p} = \boldsymbol{A}\boldsymbol{p} + \boldsymbol{c} \tag{2}$$

Vectors $\boldsymbol{p}$ and $\boldsymbol{c}$ have dimension $[N \times 1]$, where N is the total number of economic activities. From Eq. (2) it results that the total production depends on the demand of the economic sectors (given by term $\boldsymbol{A}\boldsymbol{p}$) and on a final external consumption demand (term $\boldsymbol{c}$) of the goods or services produced by the N economic activities. From Eq. (2), the final consumption can be obtained:

$$\boldsymbol{c} = (\boldsymbol{I} - \boldsymbol{A})\boldsymbol{p} \tag{3}$$

Eqs. (2) and (3) refer to the relation between production and consumption in standard IO analysis (Rose & Miernyk, 1989). However, this relation is changed in a disaster context, where the focus is on the vectors of missed production, $\Delta\boldsymbol{p}$, and unmet consumption, $\Delta\boldsymbol{c}$ (Rose et al. 1997).

4.2. Production and consumption during EPN disruption due to an earthquake event

Following the approach of Rose et al. (1997), missed production is assumed to depend on: (i) the proportion of electric power outage that in this case is the expected value, $\bar{\alpha}$, (see Section 3.3); and (ii) the adaptability of the *i-th* activity to blackouts, which is represented by a resiliency factor, f_i, $0 \le f_i \le 1$, $i = 1 \dots, N$: when $f_i = 0$, the *i-th* activity completely ceases production during a blackout; on the contrary, when $f_i = 1$, the *i-th* activity is unaffected. Then, missed production for activity i, Δp_i, is given by:

$$\Delta p_i = (1 - f_i)\bar{\alpha} p_i \qquad (4)$$

Having all Δp_i, the unmet consumption can be computed by using Eq. (5), yielding:

$$\Delta \boldsymbol{c} = (\boldsymbol{I} - \boldsymbol{A})\Delta \boldsymbol{p} \qquad (5)$$

Vectors $\Delta \boldsymbol{p}$ and $\Delta \boldsymbol{c}$ reflect two sides of the economic consequences of a disruption in electricity supply in a single geopolitical unit.

In order to model the regional economic impacts of the EPN disruption, the regionalized IO matrix $\boldsymbol{A^{reg}}$, the regionalized missed production $\Delta \boldsymbol{p^{reg}}$ and the regionalized unmet consumption $\Delta \boldsymbol{c^{reg}}$ need to be quantified, as described in what follows.

In this respect, denote as NR the number of all the N activities across R regions, and as h and k, $h, k = 1, \dots, NR$, the indexes that represent the activities i, j, with $i, j = 1, \dots, N$, in regions $r, g = 1, \dots, R$, respectively. Notice that index h (or k) replaces two indices, i.e., i (or j) and r (or g) associated with the activity and the region, respectively.

Missed production is estimated by updating Eq. (4) to this new setting. Let $\bar{\alpha}^{reg,r}$ be the proportion of electricity outage for region r. Assuming the resiliency factor of regionalized activity i depends on its trade and not on its location, its missed production is estimated as:

$$\Delta p_h^{reg} = \Delta p_i^{reg,r} = (1 - f_i)\bar{\alpha}^{reg,r} p_i^{reg,r} \qquad (6)$$

Eq. (6) associates the reduction in total production with the economic activity and where it takes place. Unmet consumption, then, is computed as:

$$\Delta \boldsymbol{c^{reg}} = (\boldsymbol{I} - \boldsymbol{A^{reg}})\Delta \boldsymbol{p^{reg}} \qquad (7)$$

If necessary, unmet consumption is cropped to meet the original production (Rose et al. 1997) to ensure that $\Delta c_h^{reg,r} \le c_h^{reg,r}$.

4.3. IO matrix construction

For a single geopolitical unit, e.g., the country-wide level, IO matrix $\boldsymbol{A}$ can be built from the normalization of the sales matrix, $\boldsymbol{S}$, between the N economic activities. Matrix $\boldsymbol{S}$ has dimension $[N \times N]$ and its element $S_{i,j}$ represents the total volume of sales, in monetary units, from activity i to activity j during a window of time (e.g., a year). Matrix $\boldsymbol{A}$ is computed from matrix $\boldsymbol{S}$ as follows:

$$A_{i,j} = \frac{S_{i,j}}{z_j} \qquad (8)$$

where z_j is the total amount of sales, including exports, sales to natural people, sales to the government, and other gains associated with activity j.

To build the regionalized IO matrix, $\boldsymbol{A^{reg}}$, of dimension $[NR \times NR]$, the regionalized sales matrix, $\boldsymbol{S^{reg}}$, of dimension $[NR \times NR]$, and the regionalized vector, $\boldsymbol{z^{reg}}$, of dimension $[NR \times 1]$, replace matrix $\boldsymbol{S}$ and vector $\boldsymbol{z}$ in Eq. (8), as follows:

$$A_{h,k}^{reg} = \frac{S_{h,k}^{reg}}{z_k^{reg}} \qquad (9)$$

Regionalized sales matrix, $\boldsymbol{S^{reg}}$, can be built from matrix $\boldsymbol{S}$ and the regional GDP by activity. This process is carried out by considering that there may be: (i) *local activities* that sell to other activities in the same region (e.g., commerce, such as shops and restaurants); and (ii) *nonlocal activities* that sell across the country (e.g., manufacturing, fishing and finance). In addition, it is assumed that sales are distributed across regions in proportion to regional shares of the activities (economic activities sell in proportion to the market share of the regions in the activities). Then, element $S_{h,k}^{reg}$, which depends on the nature of economic activities i, j with $i, j = 1, \dots, N$, in the regions $r, g = 1, \dots, R$, is computed as follows:

$$S_{h,k}^{reg} = S_{i,j}^{reg,r,g} = \begin{cases} \omega_i^r \omega_j^g S(i,j) & i\ nonlocal \\ \omega_i^r S(i,j) & i\ local, r = g \\ 0 & i\ local, r \neq g \end{cases} \qquad (10)$$

Weights $\omega_i^r = \omega_h$ and $\omega_j^g = \omega_k$ represent the relative contribution of economic activity i and j in regions r and g to the GDP; for example, weights ω_i^r is given by:

$$\omega_i^r = \frac{q_i^{reg,r}}{q_i^{all}} \qquad (11)$$

where $q_i^{reg,r}$ is the contribution of economic activity i in region r to the national GDP, whereas q_i^{all} indicates the contribution of economic activity i to the national GDP across all regions.

Having matrix $\boldsymbol{S^{reg}}$, only vector $\boldsymbol{z^{reg}}$ needs to be estimated to obtain the regionalized IO matrix, $\boldsymbol{A^{reg}}$ by Eq (9). This is simply done by weighing vector $\boldsymbol{z}$ as follows: $z_k^{reg} = z_j^{reg,g} = \omega_j^g z_j$.

Finally, notice that the regionalized total production, $p_i^{reg,r}$, in Eq. (6) is obtained by summing the column values of sale matrix $\boldsymbol{S^{reg}}$ for the region of interest.

5. Case study

In this work, the Chilean electrical power transmission system has been analyzed. With an extension of 3100 km, it covers most of the national territory from the northernmost region of Chile to the Chiloé Island in the south. It comprises 14 of the 16 Chilean regions, and serves 98.5% of the Chilean population (Coordinador, 2019a).

The model of the Chilean EPN has been constructed from several official data sources: the National Electrical Coordinator (Coordinador, 2019b), the Ministry of Energy (2019), and the National Energy Commission through its platform, Energía Abierta (2019). Details about the model construction can be found in Ferrario et al. (2019). In extreme synthesis, data refer to the year 2017 and led to the identification of 500 power generation units, 994 substations and 1195 transmission lines. In 2017, the total installed power generation capacity was 21.9 GW, the total load in this year was 68,526 GWh, and the peak load reached was 10 GW.

Figure 1 illustrates the map of Chile, divided in regions, with the Chilean power generation units (Figure 1a.), and substations and transmission lines (Figure 1b.). Figure 1 also shows the epicenters of the three selected earthquakes. Specifically, earthquakes have been selected with the same moment magnitude, M_w 8.5, and epicenters located in the north, middle and south of the country, in the subduction interface zones in the Pacific Ocean, at about 15 km from the coast with the following latitude and longitude coordinates:

(a) Northern earthquake: (-20.235°, -70.295°), in front of the cost of Tarapacá region;

(b) Central earthquake: (-33.135°, -71.871°), in front of the cost of Valparaiso region;

(c) Southern earthquake: (-39.804°, -73.575°), in front of the cost of Los Ríos region.

Details about the IO matrix built for Chile and the adopted resiliency factors are given in Section 5.1; and results of the analyses carried out are provided in Section 5.2.

5.1. *Data for the IO analysis*

5.1.1. IO matrix for Chile

Country-level IO and sales matrix data of Chile are available with respect to 111 economic activities from Banco Central de Chile (2013). These matrices have been regionalized using the procedure of Section 4.3 and the regional GDP data, disaggregated by economic activity, also available from Banco Central de Chile (2013). Sales and GDP values have been adjusted by inflation to 2019.12.31.

A scheme of 13 economic activities has been used in this work. The regional GDP is reported alongside 12 activities, one of them consisting of essential utilities, which contains electricity. Therefore, the 111-activity sales matrix was reduced to 13 activities, to match 11 activities of the regional GDP, while essential utilities was split in two categories, one comprising electricity and the other the rest of the utilities.

The resulting 13 activities are: *farm and forest*, which includes agriculture, livestock operations and forestry; *fishing*; *mining*; *manufacture*, including also product restoration; *gas, water and waste*, which also includes warm water, heating, and recycling; *construction*; *commerce*, including retail, hotels, eateries; *transportation*, including logistics, travelling, port operations, but also telecommunications; *business and finance*, which considers services such as auditing, consulting, marketing, as well as financial services; *real estate*, which includes housing services, sales, rentals; *personal services*, including healthcare, education, entertainment; *public administration*, associated with local and national governments; and *electricity*, which includes its generation, transmission and distribution.

The economic activities considered as local, which, as mentioned in Section 4.3, sell only to other activities within the same region, include the following sectors: (i) *gas, water and waste*; (ii) *commerce*; (iii) *real estate*; and (iv) *electricity*.

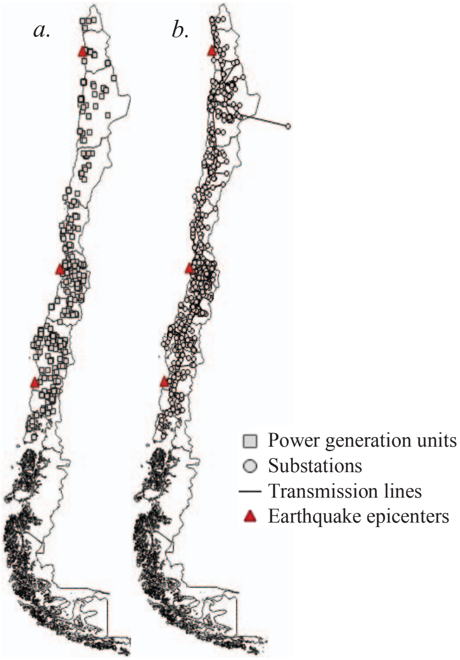

Figure 1: Map of the Chilean EPN: a) power generation units; and b) substations and transmission lines. The substation outside Chile is in Argentina.

5.1.2. Resiliency factors

Resiliency factors have been obtained from surveys in the Aichi and Shizuoka prefectures of Japan (Kajitani & Tatano, 2009). These factors indicate the likelihood the surveyed businesses could continue operating in absence of electricity supply. Reasons for business disruption include interruptions in information systems, cooling (e.g.

refrigeration), air conditioning, elevators and automatic doors, among several others. The economic categories considered in Kajitani & Tatano (2009) do not exactly match the ones used in this work, so some factors had to be repeated or combined (by geometric mean). Table 1 shows the resiliency factors used in this work.

Table 1: Resiliency factor of each economic activity.

Economic activity	Resiliency factor
Farm and forestry	0.52
Fishing	0.52
Mining	0.75
Manufacture	0.06
Gas, water and waste	0.00
Construction	0.29
Commerce	0.31
Transportation	0.40
Business and finance	0.34
Real estate	0.39
Personal services	0.35
Public administration	0.60
Electricity	0.00

5.2. *Results*

In this work, the impact of three earthquakes on the Chilean EPN and the consequences on the national economy are evaluated, disregarding effects not induced by the EPN, such as urban damage or consumption pattern changes.

For each earthquake event, $M = 10000$ scenario simulations are carried out according to the procedure illustrated in Sections 2-4. It is worth mentioning that EPN performance, in terms of unsupplied energy, has been evaluated for the first hour after the earthquake; then, since economic losses are usually estimated on an annual basis, it is assumed that losses are evenly distributed throughout the year and their values are divided for the number of hours in a year.

5.2.1. Results at national level

The national expected unsupplied energy produced by the three earthquake events is equal to 1066 [MWh], 3803 [MWh], and 842 [MWh] for earthquakes 1, 2, and 3, respectively. The corresponding expected electricity outage ratios, $\bar{\alpha}$, are 0.14, 0.48, and 0.11. The considerable higher impact of earthquake 2 is due to the epicenter being located close to the Chilean central regions, which are the most populated areas and also characterized by higher density of substations and power plants. In Table 2, the missed production (Eq. (4)) for the electricity sector, and the missed production and unmet consumption for all the N activities ($\sum_{i=1}^{N} \Delta p_i$, and $\sum_{i=1}^{N} \Delta c_i$, respectively), at national level, are reported. Results are given in millions of Chilean pesos (CLP).

As expected, the higher the outage ratio of electricity, the higher the economic losses related to missed electricity production (Table 2, second column), due to the linear relation illustrated in Eq. (4). However, it can be noticed that even though earthquake 3 causes slightly lower expected unsupplied energy than earthquake 1, it produces higher economic impacts in terms of total missed production and unmet consumption (Table 2, third and fourth columns, respectively). This may be due to the distribution of the economic activities in Chile. Indeed, mining is the main economic activity in the north, and it seems resilient to blackouts (resiliency factor of 0.75). In the south, manufacturing and personal services (hospitals, schools) are more relevant given that the south of Chile is more populated than the north. Both economic activities are much more sensitive to blackouts than mining, with resiliency factors of 0.06 and 0.35, respectively.

Table 2. Economic cost with respect to missed production and unmet consumption at national level, under each earthquake scenario, for the electricity sector and all the sectors.

Earthquake	Missed production – electricity [10^6 CLP]	Missed production – all sectors [10^6 CLP]	Unmet consumption – all sectors [10^6 CLP]
1	120	1378	1198
2	449	14576	9134
3	100	2877	2063

5.2.2. Results at regional level

Fig. 2 illustrates the expected electricity outage ratio, $\bar{\alpha}^{reg,r}$, together with the upper and lower quartile, in each region r, for each of the three earthquakes. Regions in the Figure are reported in order from north to south, from left to right. The most impacted regions are those close to the epicenter; indeed, these regions almost reach a complete electricity outage with outage ratios close to 100%. Notice that the impact of the earthquake seems to have a local effect given that it does not spread across the entire country. Overall, earthquake 2 (Central Chile), induces the largest service disruptions.

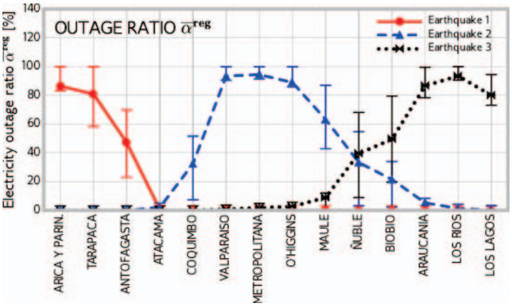

Figure 2: Percentage of the expected electricity outage ratio, $\bar{\alpha}^{reg,r}$, at regional level for the three earthquake events. Whiskers represent the upper and lower quartiles.

Economic impacts have been estimated in terms of missed production and unmet consumption at regional level for each of the 13 activities and for all the activities together. However, for space limitation, in Fig. 3, only economic losses considering all the activities (Figs. 3a and 3b), the farm and forestry activity (Figs. 3c and 3d), and the mining activity (Figs. 3e and 3f), are given in terms of missed production (on the left) and unmet consumption (on the right).

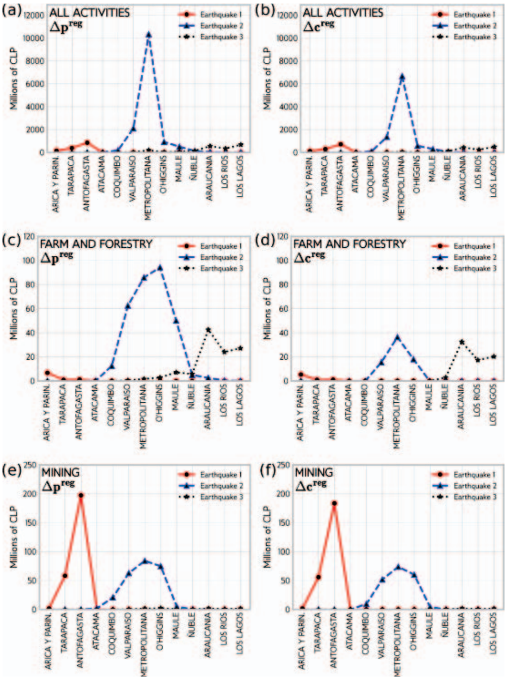

Figure 3: Missed production (on the left) and unmet consumption (on the right) for all activities (a and b), farm and forestry activity (c and d), and mining activity (e and f), under each earthquake scenario.

It can be noticed that earthquake 2 concentrates most of the missed production and unmet consumption (Fig. 3a and 3b) in the Metropolitana region, which hosts about 45% of the population of the country. This explains why earthquake 2 is associated with disproportionate economic impacts when compared to the other earthquakes, as shown in Table 2.

Production and consumption of the goods produced by the farm and forestry activity (Figs. 3c and 3d) do not occur in the same regions. In earthquake 2, for example, production in the Coquimbo and Maule regions is affected, while consumption is not. Moreover, production is most affected in the O'Higgins region, while consumption is most affected in the Metropolitana region. This suggests that affectation of the farm and forestry economic activity mostly propagates to other regions and economic activities of Chile.

The similarity of Figs. 3e and 3f is a result of the relative independence of the mining activity with respect to the rest of the economy. Mineral production in Chile is exported almost completely. Nevertheless, this does not mean that variations in mineral production (exports) have no effect on the rest of the national economy; in fact, mineral exports strongly influence exchange rates between Chilean pesos (CLP) and other currencies, which, in turn, affects imports and, hence, the rest of the economy. Such a dynamic is not captured by the IO model, because it does not consider price fluctuations in its structure.

This model suggests that economic affectation (Fig. 3) is confined to the regions closer to the earthquake epicenter (Fig. 2). This is confirmed by the results of the rest of the economic activities, which are not shown here. Economic affectation does not seem to propagate further than electricity outage; in production, this is explained by Eq. (6), but it repeats in consumption, which is obtained using Eq. (7). This downplay of interdependencies may disappear if another estimation method is used.

6. Conclusion

This study estimated the economic losses induced by the reduction of functionality of the Chilean EPN when subjected to three M_w 8.5 earthquake events located in the north, the center, and the south of Chile. Earthquake impacts on the EPN were given as expected unsupplied energy and the economic losses were estimated for 13 economic sectors of Chile. The analysis has been performed both at the national and regional level and showed that economic impacts strongly depend on the earthquake epicenter and the main economic activities developed in each region. It is worth mentioning that the EPN is here the only system exposed to the occurrence of strong earthquake events, since the focus of the analysis is on the propagation of the impacts to the electric power system itself and to the interconnected economic sectors. This inevitably underestimates the total impacts on the society in real situations in which all the infrastructures and economic sectors are affected at the same time by the occurrence of earthquakes.

This work presents several limitations concerning some assumptions made and the use of the IO model itself. In particular, the unsupplied energy of the EPN has been evaluated only for the first hour after the earthquake, neglecting the entire recovery process, thus underestimating the total economic impacts. These impacts may be misestimated also for some limitations associated with the IO model; indeed, the linearity assumption, in particular, neglects price dynamics associated with changes in supply and demand, and ignores inventory effects. This may lead to under- and over-estimations of missed production and unmet consumption. This is why missed production may be estimated to be greater than the original production (Rose et al 1997). Finally, the only interdependencies captured by the model are those related to supply chains, in which one economic activity provides supply to the others economic activities.

Future work will analyze the economic impact in greater detail and will attempt to overcome some limitations of the present work, such as considering full SPRA with stochastic earthquake generation, including the recovery of the EPN in the impacts, and further elaboration on economic impact assessment methods.

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References

Abrahamson N., Gregor N., Addo, K. (2016). BC Hydro ground motion prediction equations for subduction earthquakes. *Earthquake Spectra*, 32(1), 23-44.

Banco Central de Chile (2013). Estadísticas en Excel: Compilación de Referencia. https://si3.bcentral.cl/estadisticas/Principal1/Excel/CCNN/cdr/excel.html

Coordinador (2019a). www.coordinador.cl/sistema-electrico/ Coordinador Eléctrico Nacional. Last access March 2019.

Coordinador (2019b). https://infotecnica.coordinador.cl/ Coordinador Eléctrico Nacional. Last Access March 2019.

Energía Abierta (2019). http://energiaabierta.cl/ Energía Abierta. Last access March 2019.

EPRI (2013). Seismic probabilistic risk assessment - Implementation guide. Final Report 3002000709, EPRI, Palo Alto, CA.

FEMA (2003). Hazus-MH 2.1 Technical Manual. Department of Homeland Security, Federal Emergency Management Agency, Mitigation Division Washington, D.C.

Ferrario E., Poulos A., de la Llera J. C., Lorca A., Oneto A. and Magnere C. (2019). Representation and Modeling of the Chilean Electric Power Network for Seismic Resilience Analysis. *29th European Safety and Reliability Conference*. Hannover, Germany.

Goda K., and G.M. Atkinson (2010). Intraevent spatial correlation of ground-motion parameters using SK-net data. *Bull. Seismol. Soc. Am. 100(6)*, 3055-3067.

Haimes Y. Y., and Jiang P. (2001). Leontief-based model of risk in complex interconnected infrastructures. *Journal of Infrastructure Systems*, 7(1), 1-12.

He P., Sheng N T., Su B. (2019). Energy-economic resilience with multi-region input–output linear programming models. *Energy Economics* 84, 1-14.

Jayaram N. and J.W. Baker (2010). Efficient sampling and data reduction techniques for probabilistic seismic lifeline risk assessment. *Earthq Eng Struct Dyn* 39, 1109–1131.

Kajitani Y, Tatano H (2009). Estimation of Lifeline Resilience Factors Based on Surveys of Japanese Industries. *Earthquake Spectra* 25(4): 755-776.

Koks E. E., Carrera L., Jonkeren O., Aerts J. C. J. H., Husby T. G., Thissen M., Standardi G., Mysiak, J. (2016). Regional disaster impact analysis: comparing Input-Output and Computable General Equilibrium models. *Natural Hazards and Earth System Sciences*, 16, 1911-1924.

Koks E. E., and Thiessen M. (2016). A Multiregional Impact Assessment Model for disaster analysis. *Economic Systems Research* 28(4), 429-449.

Li B., Barker K., Sansavini G. (2018). Measuring Community and Multi-Industry Impacts of Cascading Failures in Power Systems. *IEEE Systems Journal*, 12(4), 3585-3596.

Miller R. E. and P. D. Blair (2009). *Input-output analysis: foundations and extensions.* Cambridge university press.

Ministry of Energy (2019) sig.minenergia.cl/sig-minen/moduloCartografico/composer/ Ministerio de Energía. Last Access March 2019

Okuyama Y. and J. R. Santos (2014). Disaster impact and input–output analysis. *Economic Systems Research 26(1)*, 1-12.

Pant R., Barker K., Hank Grant F., Landers T. L. (2011). Interdependent impacts of inoperability at multi-modal transportation container terminals. *Transportation Research Part E: Logistics and Transportation Review* 47(5), 722-737.

Poulos A., S. Espinoza, J.C. de la Llera, and H. Rudnick (2017). Seismic Risk Assessment of Spatially Distributed Electric Power Systems. *16th World Conf. on Earthquake Engineering*, Santiago, Chile.

Rose A. (2004). Economic principles, issues, and research priorities in hazard loss estimation. in Y. Okuyama and S. Chang (Editors), Modeling Spatial and Economic Impacts of Disasters, Springer-Verlag, New York, 13–36.

Rose A., Miernyk W. (1989). Input-output Analysis, the First Fifty Years. *Economic Systems Research*, 1(2), 229-268.

Rose A., Benavides J., Chang S. E., Szczesniak P., Lim D. (1997). The Regional Economic Impact of an Earthquake: Direct and Indirect Effects of Electricity Lifeline Disruptions. *Journal of Regional Science* 37(3), 437-458.

UNISDR (2015). Global Assessment Report on Disaster Risk Reduction. Country risk profile. United Nations Office for Disaster Risk Reduction.