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3 **Quantifying restoration time of power and telecommunication** 4 **lifelines after earthquakes using Bayesian belief network model**

5 Melissa De Iuliis^a, Omar Kammouh^b, Gian Paolo Cimellaro^c, and Solomon Tesfamariam^d

6
7 ^aPhD. Candidate, Dept. of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso
8 Duca degli Abruzzi, 24, Torino, Italy, Email: melissa.deiuliis@polito.it

9 ^bPostDoc, Dept. Materials, Mechanism, Management and Design, Delft University of Technology,
10 Stevinweg 1, 2628 CD Delft, Netherlands, Email: o.kammouh@tudelft.nl

11 ^cAssociate Professor, Dept. of Structural, Geotechnical and Building Engineering, Politecnico di Torino,
12 Corso Duca degli Abruzzi, 24, Torino, Italy (Corresponding author), Email: gianpaolo.cimellaro@polito.it

13 ^dProfessor, School of Engineering, The University of British Columbia, 2329 West Mall, Vancouver, BC,
14 Canada, Email: solomon.tesfamariam@ubc.ca

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Abstract

18 Natural and human-made disasters can disrupt infrastructures even if they are designed to be hazard resistant. While the
19 occurrence of hazards can only be predicted to some extent, their impact can be managed by increasing the emergency
20 response and reducing the vulnerability of infrastructure. In the context of risk management, the ability of infrastructure
21 to withstand damage and re-establish their initial condition has recently gained prominence. Several resilience strategies
22 have been investigated by numerous scholars to reduce disaster risk and evaluate the recovery time following disastrous
23 events. A key parameter to quantify the seismic resilience of infrastructures is the *Downtime* (DT). Generally, DT
24 assessment is challenging due to the parameters involved in the process. Such parameters are highly uncertain and
25 therefore cannot be treated in a deterministic manner. This paper proposes a Bayesian Network (BN) probabilistic
26 approach to evaluate the DT of selected infrastructure types following earthquakes. To demonstrate the applicability of
27 the methodology, three scenarios are performed. Results show that the methodology is capable of providing good
28 estimates of infrastructure DT despite the uncertainty of the parameters. The methodology can be used to effectively
29 support decision-makers in managing and minimizing the impacts of earthquakes in immediate post-event applications
30 as well as to promptly recover damaged infrastructure.

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Keywords: Downtime, Restoration, Lifelines, Infrastructure, Bayesian Networks

1. Introduction

Past global earthquake events, e.g. 1994 Northridge and 2016 Kaikoura earthquakes, have led to the functional disruption of power and telecommunication networks [1-3]. In the 1994 Northridge earthquake that struck Los Angeles, around 2.5 million customers lost electric power [1], with a consequent blackout of the city. Failures of electric power networks and grids can cause severe and widespread societal and economic disruption [4]. A continuous power supply is also crucial for other networks since it supplies primary and secondary energy. For example, the transportation system relies on the power network for its signals and switches; the natural gas and water systems depend on the electric power to operate their components, such as control switches and pumps, respectively; and finally, the telecommunication network relies heavily on the power network to supply power to its communication switches. The communication networks are important in post-disaster scenarios when the services are most needed to carry out relief management tasks as well as to facilitate repairs for critical infrastructure [3, 5]. Maintaining proper operation of critical infrastructures is, therefore, a primary challenge that has aroused attention to the seismic safety of lifeline systems. Furthermore, studying the resilience of critical infrastructures that are prone to many disruptive events or inadequate maintenance can be used to evaluate the functionality and the ability of an infrastructure to provide its service under emergency conditions [6, 7].

In engineering, the concept of resilience is defined as the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways to minimize social disruption and mitigate the effects of further earthquakes [8]. Wagner and Breil [9] defined resilience as the ability to “withstand stress, survive, adapt, and bounce back from a crisis or a disaster and rapidly move on”. In the seismic resilience assessment context, downtime (DT) can be defined as the time between the moment the hazard event occurs (t_o), where the functionality of the system $Q_{(0)}$ drops to $Q_{(t)}$, to the time when the functionality is completely restored (t_1) [10, 11] (see Figure 1). Comerio [12] described DT as “the time necessary to plan, finance, and complete repair facilities damaged by earthquake or other disasters and it is the sum of rational and irrational components”. In this paper, the downtime is defined

58 as the period required to restore the functionality of a structure or infrastructure systems (e.g., power network,
59 water supply, community) to its initial condition before a severe event [8].

60 **Figure 1.** Conceptual resilience function of a system highlighting Downtime (DT) (adapted from [10])

61 Several methodologies have been investigated in the literature to quantify the downtime of buildings and
62 infrastructures after disruptive events [6, 12]. For example, the Federal Emergency Management Agency
63 (FEMA) has performed several studies to estimate earthquake loss of buildings through the *Performance*
64 *Assessment Calculation Tool* (PACT) [13]. PACT is an electronic tool that performs probabilistic computation
65 and an accumulation of losses for individual buildings by using fragility and consequence data. Almufti and
66 Wilford [14] presented the *Resilience-based Earthquake Design Initiative* (REDI™), which is a tool based on
67 the results from PACT. Their methodology provides a framework that implements a resilience-based
68 earthquake design to achieve much higher performance. Besides, a performance-based earthquake method to
69 evaluate DT of infrastructures using fault trees was presented in [15]. Fault trees have long been used to
70 estimate the probabilistic time needed to restore a facility through a database of component damageability and
71 repair-time data.

72 The DT can be affected by different factors, **predictable** and **uncertain**. The **predictable factors** are easily
73 quantifiable, such as construction costs and repair time, whereas the “**uncertain**” factors consider the time for
74 mobilizing human and economic resources. These uncertain factors, such as *finance and bidding process,*
75 *financing planning, availability of the human resource, and regulatory and economic uncertainty,* are
76 important factors that need to be considered in the definition and estimation of the downtime [12]. Although
77 several studies have been carried out to quantify DT, still few models take into account the contribution of
78 **uncertain** factors due to the uncertainty (e.g. imprecision and vagueness) and difficulty involved in their
79 quantification [16, 17]. Indeed, **uncertain** parameters could vary significantly depending on the condition of
80 the affected area. Moreover, immediate post-event actions and decisions are often made under great
81 uncertainty, due to the limited availability and quality of information. This leads decision-makers to act in the
82 chaotic post-disaster environment by counting on limited and uncertain information and on their personal
83 experience [18].

84 The uncertainties and interdependencies involved in the DT assessment make hierarchical/graphical models a
85 viable alternative [19, 20]. Over the years, Bayesian networks (BNs) have been explored to account for
86 probabilistic uncertainties and complete interaction of the decision variables. BNs are popular tools for
87 modeling uncertainty and complex domains and for integrating different sources of information such as
88 observed data and expert judgment [21].

89 The BN is efficient for handling risk assessment and decision-making under uncertainty [22]. It has been used
90 in: risk analysis [23], resiliency modelling [24-28], reliability engineering [29, 30], and safety management
91 [31-33]. Johansen and Tien [34] used BN to model interdependencies between critical infrastructures (such as
92 water, power, transportation, communication, and fuel networks). Cai, Xie [25] utilized BN to quantify a
93 resilience metric for different types of engineering systems (e.g. mechanical engineering, civil engineering,
94 critical infrastructure, etc.). The proposed resilience metric can be used either to optimize or to design
95 engineering systems against various hazards, such as earthquakes, floods, etc. proposed a framework to
96 evaluate the resilience through the BN in a quantitative manner. The method allows modeling and predicting
97 the resilience of engineering systems in the design and maintenance phases. Hosseini and Barker [26]
98 introduced a resilience quantification methodology using BN with the application on inland waterway port.
99 Several other examples of BN applications in engineering decision making are reported in the literature [35].
100 However, most of the existing BN methods for resilience quantification cannot evaluate the DT for
101 infrastructures. The research in DT assessment of infrastructures through BN models is still at an early stage
102 and a consistent and comprehensive methodology that considers both [predictable](#) and [uncertain](#) components
103 for analyzing the DT of infrastructures in response to various hazards is still missing. Thus, there is a pressing
104 need to develop a methodology to evaluate the recovery time of lifelines to restore their functionality and
105 decrease their vulnerability to future severe events.

106 The main objective of this research is to develop an assessment model to evaluate the DT of lifelines following
107 earthquakes to deal with uncertainties, including randomness and ignorance. For this purpose, this study
108 proposes a BN-based assessment method that combines the effects of [predictable](#) and [uncertain](#) parameters,
109 such as technical, engineering, and social components. The proposed DT model benefits of the BN potentials,
110 including accounting for uncertainty and inference analysis to develop a general decision support framework
111 that can be used under emergency conditions to (i) take into account those [uncertain](#) parameters that have a

112 high impact on the recovery process and that are tricky to quantify, (ii) estimate the downtime of power and
113 telecommunication networks damaged by earthquakes, and (ii) to help decision-makers prioritize financial
114 resources during the planning and management post-disaster strategies through analyzing different what-if
115 scenarios. The framework can be used to update probabilistic information of the parameters involved in the
116 DT assessment. Updating information helps support critical decisions in the aftermath of an earthquake.
117 The remainder of this paper is structured as follows: Section 2 is dedicated to reviewing the basic knowledge
118 of the BN. Section 3 illustrates the DT framework and the key variables that are identified from past studies
119 and describes the fragility curves designed for estimating conditional probabilities. Section 4 introduces the
120 sensitivity analysis performed to identify critical inputs. Section 5 presents an illustrative example to
121 demonstrate the applicability of the DT framework. Finally, section 6 concludes and proposes future work.

122 **2. BBN framework for the downtime assessment of infrastructures**

123 **2.1. The methodology**

124 The methodology proposed in this work can be divided into the following:

- 125 • DT modeling: a BN hierarchical model is developed to quantify DT. The DT key variables and
126 connectivity of the BN are obtained through expert knowledge and published articles.
- 127 • Conditional probabilities (CPs): CPs for the child variables are obtained from historical data, expert
128 judgment, and published literature. For the final output (i.e. DT), conditional probabilities are obtained
129 using restoration fragility curves derived from a database for past seismic events.
- 130 • Inference: the last step of the methodology is the combination of the key variables through the
131 inference system of BN to obtain the final output of the network (i.e. the DT).

132 **2.2. Background of Bayesian Network**

133 The Bayesian Network (BN), also known as Bayesian Belief Network or Causal Probabilistic Network,
134 belongs to the family of probabilistic *graphical models* (GMs). It is based on Bayes' theorem that permits
135 graphical probabilistic relationships among a set of variables [36]. The uncertainties in a BN model can be
136 expressed through subjective probabilities [30, 36], thus making the approach suitable for experts' knowledge.
137 BNs are suitable tools for computing the probability distribution of variables conditioned on some variables

138 that have been observed through both quantitative and qualitative information [26]. Variables of a BN can be
139 Boolean (yes, no), continuous, or qualitative (low, medium, high)). A BN includes:

- 140 1. A set of random variables that can be linked to each other by a set of links indicated by arrows;
- 141 2. A set of mutually exclusive states assigned to each variable (e.g. L, M, and H) describing possible
142 events that can occur;
- 143 3. A conditional probability table for each child node and an unconditional probability table for each
144 father node.

145 An outgoing link from variable X to variable Y indicates a relationship that the variable Y (child) is dependent
146 on the variable X (parent). The set of edges and nodes defines a directed acyclic graph. The relationships
147 among the variables of a BN are usually measured by a set of Conditional Probabilities Tables (CPTs), where
148 the likelihood of the child node to assume a certain state under a given state of its parent is assigned through
149 expert knowledge [37, 38]. In the case of independent variables with no parents, the CPT is reduced to an
150 unconditional probability Table (UPT).

151 **2.3. Conditional probabilities and inference**

152 The main concept of the BN comes from the Bayes' theorem, which defines the relationship between two
153 nodes A (parent) and B (child), as follows:

$$154 \quad P(A / B) = \frac{P(B / A)P(A)}{P(B)} \quad (1)$$

155 where $P(A/B)$ is the probability of observing A given that B is true, $P(B/A)$ is the likelihood that B is observed
156 if A is true, $P(A)$ and $P(B)$ are the probabilities of observing A and B without regarding each other. $P(A/B)$ is
157 known as *posterior* probability and $P(A)$ is called *prior* probability [36].

158 Once the variables have been connected by a set of links, unconditional and conditional probabilities are
159 assigned. To establish unconditional probabilities (UPs) of parent nodes whose states are not known, the
160 principle of insufficient reasoning is assumed [35, 39], i.e. the basic inputs are assigned equal weights $1/n$,
161 where n is the number of states. For instance, if the variable X_1 is characterized by three states *Low* (L), *Medium*
162 (M), and *High* (H), the UPs would be $P(X_1 = L) = 1/3$, $P(X_1 = M) = 1/3$, $P(X_1 = H) = 1/3$ (Kabir et al. 2015).

163 The estimation of the conditional probabilities (CPs) can be obtained through expert knowledge elicitation and
164 training from existing data [40, 41], and it can be divided into three steps:

- 165 1. Prioritization of parent variables: the first step consists of defining the importance of the parent
166 variable on the child nodes by assigning a weight value to each parent node;
- 167 2. Definition of combinations: different states are identified for each variable by considering different
168 combinations of the child nodes;
- 169 3. Estimation of conditional probabilities: the last step is the estimation of conditional probabilities for
170 all defined combinations.

171 To better understand the process described above, an example is given. Consider a system with three father
172 nodes: *Urban Area*, *Mobility and Access*, and *Extreme Weather*, and a child node: *Impacted Area* variable.
173 Following the first step of the proposed procedure, variables are prioritized by their impact on the child node.
174 That is, *Urban Area* is found to be more important than the other father variables, followed by *Mobility and*
175 *Access* then *Extreme Weather*. This implies that the *Urban Area* has a higher impact on the output variable
176 (*Impacted Area*). Three different states are assigned to each of the variables. *Urban Area* (UA) is defined using
177 three discrete states, UA^L , UA^M , and UA^S , which are related to “Large” (L), “Medium” (M), and “Small” (S)
178 states, respectively. *Mobility and Access* (MA) is classified into three qualitative states, which are denoted as
179 MA^H , MA^M , and MA^E corresponding to “Hard” (H), “Medium” (M), and “Easy” (E) states respectively, and
180 *Extreme Weather* (EW) is classified into three discrete states, which are indicated as EW^{VB} , EW^B , and EW^G ,
181 corresponding to “Very Bad” (VB), “Bad” (B), and “Good” (G) states.

182 Figure 2 shows a partial set of combinations of the states of the three variables. The worst-case scenario is
183 identified by the three states: Large (for *Urban Area*), Hard (for *Mobility and Access*), and Very Bad (for
184 *Extreme Weather*). The corresponding estimated conditional probabilities for the variable “Impacted Area”
185 are: $(IA^S, IA^M, IA^L) = (0.9, 0.1, 0)$. Starting from the worst-case scenario, other possible combinations are
186 implemented to come up with the full conditional probability table of the father node given the different
187 combinations of the states of child nodes.

188 This approach will be used hereafter to estimate the conditional probabilities for all nodes of the DT network.
189 However, for the DT variable itself, a different approach is used to come up with the conditional probabilities.
190 The conditional probabilities of the DT are calculated using restoration fragility curves based on the earthquake
191 magnitude [16]. This is introduced in detail in Section 3.

192

193 **Figure 2.** A three-node network with probability tables

194

195 **3. Downtime Modeling using BN**

196 **3.1. Variables selection**

197 Based on an extensive review of previous literary publications and studies on key parameters for downtime,
198 31 indicators are selected to develop the BN for the DT estimation [42, 43]. Indicators are selected to describe
199 the framework's components in detail. Every indicator found in the literature has been collected and then they
200 are filtered to obtain mutually exclusive indicators. This has necessitated rejecting a number of indicators either
201 because they are not relevant or because they overlapped with other indicators.

202 The indicators refer to the implementation of processes, mechanisms, or policies intending to reduce risk and
203 increase recovery [16]. The steps followed to create the network are:

- 204 1. Variable identification: A list of 31 key variables to build the network is provided from literature;
- 205 2. Variable clustering: after the variables are identified, they are clustered into groups to organize them
206 appropriately;
- 207 3. Variable connection: the last step is the connection of variables using Bayesian parent-child
208 relationships.

209 The DT input parameters considered in the model along with the values and the performance measure (when
210 available) are described in Table 1, Table 2, and Table 3. Two types of variables are considered to model the
211 DT variables: (i) discrete variables and (ii) continuous variables (i.e., DT variable). Discrete variables have a
212 finite number of values. In the proposed framework, they are defined using two or three states, such as a *High*
213 state that represents a positive outcome and *Low* state that represents a negative outcome. The continuous
214 variables, on the other hand, can take infinite possible values within a given range. However, in BNs based on
215 raw data and learned by users without a field-specific expert, it is usually assumed that variables are discrete.
216 Continuous variables are mainly required in dynamic systems. Moreover, many BN algorithms are unable to
217 handle continuous variables, as they are difficult to manage in a general way [44, 45]. Thus, the DT variable
218 has been classified into intervals in such a way to treat it as a discrete one and to have a more precise DT result.

219 **3.2. Variables connectivity**

220 The graphical representation of the proposed DT assessment model is shown in Figure 3. As shown in Figure
221 3, in a hierarchical system, the child nodes become the parent nodes of other child nodes generating new child-
222 parent relationships. For the downtime model, four downtime indices are considered: (i) exposed infrastructure
223 (EI), (ii) earthquake intensity (E), (iii) available human resources (HR), and (iv) infrastructure type (I). In the
224 figure, the ellipses represent the basic input indicators that determine the indicators designed by the rectangle
225 shape. The orange color is used to highlight the four indices mentioned above. Casual relationships among the
226 downtime indicators are established based on expert knowledge and published literature. To build the DT
227 network, a conceptual linkage between the indicators is needed taking into account the interaction between the
228 indicators and the effect that each indicator has on the downtime. Indicators are clustered as follows:

- 229 • Indicators referring to building financial reserves are grouped to support effective response and
230 recovery;
- 231 • Indicators that refer to policies and plans implemented to reduce the vulnerability of the area at risk
232 are grouped together to define the availability of human resources;
- 233 • Indicators relating to the seismic event are clustered to determine the effective recovery;
- 234 • Indicators that refer to the analyzed infrastructure are combined to carry out the exposure level of the
235 infrastructure.

236 Indicators included in the DT model are described in detail in the following section.

237 **3.2.1 Exposed Infrastructure (EI)**

238 The exposed infrastructure (EI) index describes how effectively and efficiently a city can respond to recover
239 from short-term and long-term impacts. It is quantified considering the maintenance degree of the
240 infrastructure, assuming that a higher maintenance rate would lead to a lower likelihood of damages and to
241 lower recovery time. The maintenance degree of infrastructure describes the condition the infrastructure is in.
242 Infrastructures wear out with time and use, so proper and timely maintenance must be periodically conducted.
243 Neglecting proper maintenance leads to a decline in the infrastructure's condition. In line with the state of
244 infrastructure, the maintenance degree parameter is classified as *poor*, *medium*, and *good*.

245 EI index also depends on the number of served people, which is discretized into three states corresponding to
246 *low*, *medium*, and *high* number, and on how much (*high*, *medium*, and *low*) the service of the structure is
247 necessary and important in the community (a higher number of served people and higher service importance
248 result in a higher priority of intervention following a disaster). The anti-seismic technology of the structure,
249 and the type of the required recovery, which can be *easy*, *difficult*, or *very difficult* depending on the damage
250 of the infrastructure and the economic processes, are assumed in the EI index evaluation. Besides, two-node
251 states (EI^H , EI^M), corresponding to *high* (EI^H) and *low* (EI^L), are assumed to describe the Exposed infrastructure
252 (see Table 1).

253 The recovery type includes indicators representing the *financing phase* (i.e. financing and procurement
254 process), the *building phase*, the *engineer evaluation*, and the characteristic of the seismic event (i.e. the
255 *earthquake intensity*, the *event repetition*, and the earthquake hazard). The *procurement process* is the time
256 required to make an offer by an individual or business for a product or service. Procurement is used to
257 determine the specifications of the project or details of the products and services to be purchased. During an
258 earthquake condition, it is very important to shorten the procurement process in such a way as to speed up the
259 recovery process. Given the circumstances and the immediacy of the need to respond after a seismic event,
260 three different states of procurement are considered: reactive procurement (immediate response) in the event
261 of a major hazard where the standard procurement procedure is not required to follow; emergency procurement
262 is appropriate when there is no threat to loss of life and a state of emergency is taken off; finally accelerated
263 procurement is developed to fit a specific category of procurement and immediate needs [46].

264 On the other side, *finance planning* represents the time required by the expert to plan and distribute properly
265 funds and resources in the right manner. Even though it is just a matter of bureaucracy, decision making, and
266 planning, both the *procurement process* and *financial planning* may affect strongly the downtime of a certain
267 lifetime, even though the lifeline damage is not high. The *finance planning* variable is discretized as *long*,
268 *short*, and *medium-term*. The *building phase*, sub-classified in *repair effort* and *engineering consolidation*,
269 provides the recovery activities to follow for completing the rescue process; that is, all those processes of
270 design and intervention which aim to restore the structural characteristics of the structure. *Repair effort* and
271 *engineering consolidation* parent nodes are discretized in *very difficult*, *difficult*, and *easy*. Besides, the
272 *engineer evaluation*, which is the time teams of specialists (engineers for instance) need to define and compare

273 the assessments and give feedback on the potentially damaged infrastructure after the inspection, is based on
274 the quantification of the damages and on the structural inspection process, which may require a *long, medium,*
275 *or short* time.

276 Further information on the states of the EI parent nodes is given in Figure 3 and Table 1. With the consideration
277 of the process outlined in Section 2, the corresponding unconditional probability table (UPT) of each parent
278 node is defined as $1/n$, and the CPT for EI parameter and child nodes is created through subjected knowledge.

279 **3.2.2 Earthquake Intensity (E)**

280 The *earthquake intensity* (E) expresses the severity of the earthquake and the demand to which a city will be
281 subjected and plays a primary role in estimating the downtime. In the downtime model, the E parameter
282 influences both the choice of the recovery type and the result of downtime and it is defined by combining two
283 parent nodes, the *epicentral distance*, and the *earthquake magnitude*. Distance from the epicenter is related to
284 the observed damage such that the farther a system is located from the epicenter; the less damage is observed
285 to the system. The *epicentral distance* is defined as *close, far, and very far*.

286 Four groups of Richter magnitude scale are used to classify the *earthquake magnitude* node, Strong 6-6.9;
287 Major 7-7.9; Severe 8-8.9; and Violent 9-9.9. As *epicentral distance* and *earthquake magnitude* are parent
288 nodes, the corresponding unconditional tables (UPTs) are defined as $1/n= 1/3$ and $1/n= 1/4$, respectively.

289 The E node is classified into four groups of Mercalli intensity scale ranging from least perceptible to most
290 severe: Weak MMI-MMIII, Strong MMIV-MMVI, Severe MMVII-MMX, and Violent MM>MMX (Table
291 2).

292 **3.2.3 Availability of Human resources (HR)**

293 *Human resources* play an important role in natural disaster planning. Liou and Lin [47] highlighted the critical
294 role that human resource play during emergencies, through working with management, communication, and
295 adjusting employee policies. The *Human resources* parameter is influenced by three factors: the occurrence
296 of other emergencies at the same time, the availability of a structured and defined plan, and the characteristics
297 of the impacted area (i.e., *large, medium, and small* impacted area). The *planning indicator* node is used in the
298 framework to represent the emergency response and recovery planning. It can be assessed by consulting a
299 city's local planning experts, which provide subjective assessments on three possible states of the planning

300 indicator: *bad (minimal), good, and excellent*. According to Davidson and Shah [48], the *planning indicator*
301 is classified as *bad* when planning is inadequate and inactive (e.g., procedures to explain what to do, how, and
302 when are not included, roles and responsibilities of all involved parties are not established, and a plan is not
303 practiced regularly through training); planning indicator is good when it is inadequate or inactive, then it is
304 classified as excellent if planning is adequate and active.

305 The *impacted area* factor can be divided into three sub-factors: the weather conditions of the impacted area,
306 the easiness of mobility and access into the impacted area, which depends on the condition of the post-
307 earthquake transportation system and the amount of debris, and the characteristics of the urban area. The
308 *extreme weather condition* parameter describes the post-earthquake weather that could limit the response effort
309 and make hard the condition of casualties. The *extreme weather* indicator is expressed in terms of the
310 temperature (e.g. 90°F and 32°F) [48].

311 The *urban area* is discretized as a *large, medium, and small* size according to the number of its population.
312 That is, the urban area is large-size if the population is 1.5 million or more; medium-size urban area if its
313 population is between 200,000 and 500,000; and small urban area if the population ranges between 50,000 and
314 200,000 [49]. Besides, the *urban area* parameter is identified by *Per Capita Gross Domestic Product*
315 (PCGDP), which is the indicator of a nation's living standards, the quantity of *population* of the impacted area,
316 and the *urbanization degree* [39, 50, 51]. Two nodes states (HR^L , HR^H), corresponding to *low* and *high*
317 respectively, are used to describe the Availability of human resources. Further information on the states of the
318 EI parent nodes is given in Table 3. The CPT for HR and HR sub-parameters is created in the same way
319 described before.

320 **3.2.4 Infrastructure Type**

321 Another variable that should be considered is the type of affected infrastructure since DT changes according
322 to it. It influences the required recovery type and the final output. In the proposed network (Figure 3), two
323 types of infrastructures are considered: power network and infrastructure lifelines. The corresponding UPT for
324 *Infrastructure type* is generated following the same procedure for the *Earthquake magnitude* node.

325 **3.3. Inference**

326 The downtime indicators described above can be grouped and connected through the inference process. BN's
327 structure learning and inference for the DT are performed using the commercially available product Netica
328 software [45]. This software can be used to classify and analyze data of a particular uncertain domain.
329 Construction of BNs through Netica requires a list of uncertain variables, the possible states of discrete
330 variables and possible ranges of continuous variables, the relationship among the variables, and the conditional
331 probabilities to evaluate the dependencies. Once the variables and the corresponding states/ranges and
332 probabilities have been assigned, it is possible to compile the network. To make a prediction, it is a simple
333 matter of moving over parent nodes and select a state of those nodes.

334 The BN of the DT built using the Netica user interface is presented in Figure 3. Netica solves the network by
335 finding the marginal posterior probabilities that some parameter will be in a particular state given the input
336 parameters, the conditional probabilities, and the combinations of probabilities (e.g., 37.8 (*very difficult*), 41.7
337 (*difficult*), and 20.6 (*easy*) for Building phase node) [52].

338 Whenever the probability distribution in one of the root nodes is changed, the ability to quickly test many
339 potential states and recalculate the probability distributions of all child nodes make Netica particularly useful
340 for such analyses. Using Netica, 33 nodes (20 parent or independent nodes and 12 child or dependent nodes),
341 33 links, and 844 conditional probabilities are generated.

342 Although one BN model is designed to estimate the DT for two types of infrastructure (power and
343 telecommunication system), different results are obtained by changing the infrastructure type node (i.e., power
344 or telecommunication) since the conditional probabilities used in the downtime node follow the infrastructure
345 type. Thus, changing the infrastructure type changes the model, while the other nodes remain the same in the
346 BN model.

347 **Figure 3.** Downtime assessment model for power and telecommunication infrastructures

348 **3.4. Data collection**

349 In the context of this work, recovery implies returning full service to the population. Appendix A lists the
350 complete database used to create the restoration curves of the lifelines. The database was collected only from
351 published literature for earthquakes that have occurred after the '60s because there was little or no reliable

352 information about the damage caused by earlier earthquakes. Infrastructure damage data is available in the
353 literature in both qualitative and quantitative forms. However, only reports with numerical data reporting the
354 actual time needed to restore the infrastructure service have been considered in the analysis. Qualitative data
355 has been excluded since it refers to the degree of damage to the infrastructures and not the restoration function.
356 The normalization of the data was not necessary since it is provided in the same scale (i.e., number of days
357 necessary to restore the infrastructure service) and can be easily combined [16]. For instance, the raw data of
358 the Valdivia earthquake that hit Chile in 1960 was extracted from [53]. The shock, with a magnitude of 9.5
359 on the Richter scale and an intensity of XI to XII on the Mercalli scale, led to a tsunami that disrupted Valdivia
360 city. One electrical system was damaged by the earthquake and its functionality was restored in five days. The
361 water system was also disrupted, and it took 50 days to recover its function. The gas and telecommunication
362 infrastructures performed quite well, and no damage was reported. From Appendix A, it is evident that each
363 earthquake has caused damage to more than one infrastructure system at the same time. For example, in the
364 city of Loma Prieta, the earthquake caused damage to ten water, two power, five gas, and six
365 telecommunication networks. The damaged systems needed different times to recover even when the
366 infrastructures are of similar types. For instance, the two power plants that were affected by the Loma Prieta
367 earthquake needed 2 and 0.5 days respectively to recover. There were some cases where either the damage
368 information was not available, or no damage was recorded. Such cases are marked with a dash (-) inside the
369 table. In total, the number of affected infrastructure units analyzed in this paper are 63 power systems; 84 water
370 systems; 47 gas systems; and 34 Telecommunication systems. The seismic events considered in the study are
371 with a magnitude range between M6 and M9.9. Most of the events considered took place in the USA, Japan,
372 and South America.

373 Data used to construct the restoration curves of the Power and Telecommunication systems have been divided
374 into 4 sets based on the earthquake intensity. Although it is not the only parameter, the earthquake intensity
375 plays a primary role in defining the infrastructure damage and the restoration time. This classification assumes
376 that the earthquake magnitude is fully correlated with the induced damage. The collected data has been
377 classified under four groups of Richter magnitude scale (Strong 6-6.9; Major 7-7.9; Severe 8-8.9; and Violent
378 9-9.9). While in literature other intensity measures are usually used to identify the earthquake intensity (i.e.,

379 PGA, PGD, Sa, and Sd), in this work, it was not possible to know those intensity measures for all the events
380 as such information was not published.

381 For each lifeline, a group of restoration curves considering the four magnitude ranges have been developed.
382 Table 5 presents the data sets considered in the analysis, extracted from Appendix A. The parameters
383 considered to plot the curves are: (i) the number of days required to restore full service to customers (horizontal
384 axis) and (ii) the probability that the utility is completely restored to the customers (vertical axis).

385 3.5. Fitting analysis

386 Data gathered in the form of restoration curves are fitted with three statistical distributions: gamma,
387 exponential, and lognormal cumulative distributions. Figure 4 shows the frequency histogram of the DT data
388 and the probability density function (PDF) of the gamma, exponential, and lognormal distributions related to
389 (a) the power network infrastructure and (b) the telecommunication network for earthquake magnitude range
390 EM 6-6.9.

391 **Figure 4.** Histograms and PDF fitting distributions for (a) the power infrastructure, and (b) the telecommunication infrastructure for
392 the data related to earthquake magnitude range M6-6.9

393 As shown in Figure 4, the gamma, exponential, and lognormal distributions are plotted against the empirical
394 data to visualize the distribution fit. Since the plotted PDFs present a similar trend, it is not simple to choose
395 the distribution with the best fit relying only on visual interpretation. Therefore, the goodness of fit tests
396 (GOFs) are used to identify the appropriate distribution for the empirical data. GOF of a statistical model is a
397 technique that describes how well a model fits a set of observations. It also summarizes the discrepancy
398 between the observed values and the values coming from the model [54]. The distribution with the best fit has
399 been identified through two tests: the Kolmogorov-Smirnov (K-S) and Chi-Square tests for Goodness-of-fit.

400 Results from the GOF tests are presented in Table 6 and Table 7. Results show that the gamma distribution is
401 the distribution with the optimal fit. For the power network, the gamma distribution has the lowest values of
402 D_n (K-S parameter) and χ^2_f (Chi-Square parameter) compared to the other distributions and these values are
403 lower than the corresponding critical values D_n^a and $C_{1-a,f}$. In the case of the telecommunication network, all
404 three distributions can be implemented to represent the DT data since all three distributions show lower values

405 of D_n and χ^2_f compared to the corresponding D_n^a and $C_{1-a,f}$ where the gamma distribution has the lowest
406 values. Therefore, the gamma distribution is selected to fit the DT data since it is suitable to represent the data
407 of both infrastructure systems. The gamma distribution is defined using two parameters, alpha, and beta. Such
408 parameters have been estimated for each earthquake magnitude group using the method of *maximum likelihood*
409 (ML). ML allows identifying for a set of data the probability of obtaining that set of data given the chosen
410 probability distribution model. The gamma parameters for the power and telecommunication lifelines are
411 presented in Table 8.

412 The restoration curves for power and telecommunication infrastructures are plotted using two factors: (i) the
413 number of days needed to restore full service (horizontal axis); (ii) the probability of a complete restoration
414 (vertical axis). The restoration curves are classified under four groups of Richter magnitude scale: 6-6.9 *Strong*,
415 7-7.9 *Major*, 8-8.9 *Severe*, and 9-9.9 *Violent*, as shown in Figure 5.

416 **Figure 5.** Restoration curves of (a) the power infrastructure, and (b) the telecommunication infrastructure based on earthquake
417 magnitude

418 Restoration curves are built without taking into account the attenuation function. Indeed, it is assumed that
419 infrastructures are at an equivalent distance from the epicenter. Therefore, as mentioned before, the distance
420 from the epicenter has been included in the downtime model as an extra node.

421 As shown in Figure 5, restoration curves intersect each other. In standard fragility analysis, the intersection of
422 fragility functions for different damage states within the same data should not happen. It could happen when
423 each fragility curve corresponding to a specific damage state is fitted independently of one another. To avoid
424 the intersection of fragility curves, usually, the same standard deviation for all the fragility curves is assumed.
425 In loss evaluation, however, fragility function may intersect since losses do not always follow a specific pattern
426 (e.g. a lower damage state may require more cost to be repaired) [16]. This justifies the intersection of
427 restoration curves in Figure 5.

428 **3.6. Downtime conditional probabilities**

429 Once the restoration curves are developed, the estimation of probabilities for the DT output is carried out. Five
430 intervals (e.g. states) are introduced to discretize the DT output (see Table 4).

431 A conditional probability can be obtained for every couple “DT state-earthquake intensity”. For instance,
432 assume the value for the DT is classified as *High* (25-40 days), the corresponding probabilities of recovery for
433 the power and telecommunication systems that are hit by a *Strong* earthquake (M6-6.9) are 1 and 0.97,
434 respectively (Figure 5). [The DT conditional probabilities for the power and telecommunication lifelines are](#)
435 [listed in Table 9. In Table 9 some values overlap since restoration curves intersect each other, as is explained](#)
436 [above.](#)

437 It is important to note that in this study the DT variable is assumed to be directly influenced by four variables:
438 *Infrastructure type, earthquake intensity, infrastructure exposure, and available human resources* (Figure 3).
439 The results obtained from the restoration curves correspond to *high* infrastructure exposure and *low* available
440 human resources, and they are considered baselines for estimating the probabilities for other combinations in
441 the CPT of DT. Table 10 presents a portion of the conditional probability table of the DT variable. In those
442 tables, the baselines resulted from the restoration curves are highlighted in bold and they are the starting point
443 for estimating other combinations. The conditional probabilities of other combinations in Table 10 are
444 estimated respecting that the horizontal sum must be equal to one (second probability axiom) (Figure 6). In
445 Figure 6, best-case (favorable) combinations make the probability mass function (PMF) shift to the left, which
446 implies an increase in the probability of quick recovery. The worst-case (unfavorable) combinations, on the
447 other hand, shift the PMF to the right causing a decrease in the quick recovery probability. As shown in Figure
448 6, the three distributions are the same, the only difference lies in the location of the mean value of each of the
449 three distributions that define if the scenario is favorable or unfavorable.

450 **Figure 6.** Probability mass distribution of the baseline, best-case combination, and worst-case combination.
451

452 **4. Sensitivity analysis**

453 BN analysis applies prior conditional probabilities to estimate model output in the presence of new evidence.
454 Sensitivity analysis is carried out to identify critical input parameters that have a significant impact on the
455 output result [35]. Sensitivity analysis assumes that the input parameters are uncertain. It allows identifying
456 the variation in the system’s reliability given a variation in the inputs values [55]. It also refers to how sensitive
457 the performance of a model is to minor changes in the input parameters [56]. Different methods have been
458 introduced in the literature for implementing sensitivity analysis in a BN [36, 57-60]. Since the input

459 parameters considered in the DT framework have discrete and continuous values, the variance reduction
 460 method is utilized [36, 45, 61]. The variance reduction method allows identifying the sensitivity of a BN's
 461 output to a variation in a given input by computing the variance reduction of the expected real value of a query
 462 (target) node Q (e.g. downtime parameter, DT) due to a finding at varying variable node F (e.g., *Earthquake*
 463 *intensity*, *Infrastructure type*, *Recovery type*, and *Epical distance*). The variance of the real value of Q
 464 given evidence F , $V(q|f)$ is computed using the following equation [36, 45, 62]:

$$465 \quad V(q|f) = \sum_q p(q|f)[X_q - E(Q|f)]^2 \quad (5)$$

466 where q = state of the query node Q , f = state of varying variable node F , $p(q|f)$ = conditional probability of q
 467 given f , X_q = value corresponding to state q , and $E(Q|f)$ = expected real value of Q after the new finding f for
 468 node F . By selecting the query node and choosing Sensitivity to Findings in Netica, a report will be displayed
 469 indicating how much the query node would be influenced by a single finding at each of the other nodes (varying
 470 nodes) through different sensitivity measures (i.e., variance reduction and percent contribution) [36, 45].

471 The results of the sensitivity analysis for the DT due to a finding at another node are presented in Table 11 and
 472 Figure 7. Only variables (parent and child nodes) showing a significant contribution towards the DT output
 473 have been indicated (i.e. earthquake magnitude and intensity, infrastructure type, recovery type, planning
 474 indicator, and epicentral distance). Results show that the intensity of the earthquake has the highest percent
 475 contribution towards the DT (i.e., 0.574%). The impact of the earthquake intensity is also evident in Figure 5,
 476 where the DT mostly follows the earthquake magnitude.

477 The type of analyzed infrastructure has also a high impact on the output. That is, the infrastructure type
 478 parameter shows a sensitivity of 0.569%. This result is reasonable, since in general the power network is the
 479 first lifeline to recover its functionality to supply other infrastructure systems, and consequently the DT is
 480 lower than other lifelines. The recovery type and the epicentral distance have lower sensitivities, 0.0428%, and
 481 0.0327%, respectively. Having reliable data on these key indicators is crucial to reduce uncertainty.

482 Inference analysis is also performed to evaluate the effects on the target node (i.e., the downtime) by setting
 483 best- and worst-case scenario values of the *earthquake intensity*, *epical distance*, *recovery type*, and
 484 *infrastructure type*. This is helpful in decision-making to prioritize activities to best affect desirable or to avoid
 485 undesirable outcomes. In the best scenario all the indicators are set to their optimal states, while in the worst

486 scenario the worst states are selected. Results obtained from the inference analysis are shown in Table 12.
487 From the table, it is evident that the downtime is lower in the best-case scenario than the worst-case scenario,
488 as expected. Moreover, the downtime for power infrastructure is always lower than telecommunication in both
489 the scenarios. What's more, by changing the state of one node and keeping the state of the other nodes the
490 same each time, results show that the *earthquake intensity* and the *infrastructure type* parameters have a higher
491 impact towards the target node. Thus, the sensitivity to findings and inference analysis provide the same
492 results.

493 **Figure 7.** Sensitivity analysis results of the DT Bayesian network model

494 **5. Illustrative example**

495 To demonstrate the applicability of the proposed framework, three different scenarios for the power and
496 telecommunication infrastructures have been applied. The earthquakes considered in the analysis are:

- 497 1. Scenario 1: Napa earthquake, USA, 2012;
- 498 2. Scenario 2: Nihonkai-chubu, Japan, 1983;
- 499 3. Scenario 3: Illapel, Chile, 2015.

500 Napa 2014, USA: an earthquake of a magnitude of M 6.0 and a depth of 10.7 km with the epicenter located
501 approximately 6.0 km northwest of the city of American Canyon near the West Napa Fault, in the city of Napa
502 on the 24th of August 2014. Structural damage was generally concentrated on unreinforced masonry buildings
503 and residential properties. Approximately 200 people were injured, and 1 person died. Lifelines performed
504 relatively well: water infrastructure was largely restored within ten days, with the majority of breaks being in
505 cast-iron pipes. No damage was observed to the electricity transmission network, but outages in the distribution
506 system affected almost 70,000 customers. 99% of these faults were restored within 26 hours [63].

507 Nihonkai-chubu 1983, Japan: A large earthquake magnitude M7.8 occurred off the coast of Akita prefecture,
508 Japan, on the 26th of May 1983 generating a major local tsunami that was destructive in Japan as well as in
509 Korea. The event caused severe damage to the coastal areas of the Tohoku region. In particular, most of the
510 earthquake damages hit buildings and lifeline facilities. Information regarding the DT of disrupted
511 infrastructures shows that Nihonkai-chubu stayed with partial water and gas systems for around one month

512 after the earthquake due to the severe damage to the ground pipelines. The power supply, instead, was restored
513 the day after the seismic event [64].

514 Illapel 2015, Chile: a big earthquake of magnitude M8.4 shocked the Chilean town of Illapel on the 16th of
515 September 2015. The earthquake was followed by a tsunami that killed several people on the coastline. The
516 resilience and preparation of the country allowed the different lifelines system to perform properly [65].

517 The BN model built through Netica software to simulate the three different scenarios is show in Figure 8.

518 **Figure 8. The Bayesian network of the Downtime indicators using Netica software**

519 The input data of the three scenarios are obtained from the literature (see Table 1, Table 2, and Table 3) and
520 summarized in Table 13 and Table 14. While in the first scenario all the input parameters could be found, the
521 other two scenarios are implemented considering a partial availability of information. Results from the DT
522 assessment are illustrated in Figure 9, Figure 10, and Figure 11. From the analysis, the DT output mainly
523 depends on the infrastructure type and the intensity of the earthquake. These variables showed the highest
524 influence on the DT output. As expected, results demonstrate that the power network requires more time to be
525 restored when the earthquake intensity is classified as *severe* and the epicentral distance is set as *close* (scenario
526 three). Although less time is required to restore the power network in scenario two where the infrastructure is
527 hit by a *major* seismic event and it is placed *far* from the epicenter, results are similar to those obtained from
528 scenario three. This can be justified considering that partial availability of information that affects scenario
529 two and three may make results uncertain and incorrect. Moreover, interdependencies among the lifelines were
530 witnessed and can be considered as an intrinsic characteristic of the data used to design the restoration curves.
531 In general, the power system is always the first to recover its function after a hazard event. This is usually
532 because all lifelines are heavily dependent on the power network as they need the power to function. Thus, it
533 should be restored without delay. This is evident in the results as the DT of the power network is always lower
534 than the telecommunication infrastructure in all three scenarios (i.e. probability of *very low* DT for the power
535 network is higher than the telecommunication network in all three scenarios). Furthermore, in this work, it is
536 assumed that a higher maintenance degree of infrastructures would result in a lower likelihood of damages,
537 and consequently, in lower recovery time. This assumption has been confirmed by the analysis of the three
538 scenarios. That is, the maintenance rate of infrastructures is defined as *good*, *medium*, and *poor* in the three

539 scenarios respectively. The output from the simulation is lower in the first scenario (i.e., the maintenance
540 degree is good) and is higher in the last two scenarios (i.e., the maintenance degree is medium and poor).

541 In all three scenarios, we can see uncertainty in the results in the form of probability dispersion. This is typical
542 in BN analysis as the basic inputs are uncertain in the first place. The probability dispersion or variance can
543 decrease when more data is available. For example, when data is not available, the principle of insufficient
544 reasoning is applied for the basic inputs. This means that the states of the inputs are assigned an equal
545 probability of occurrence. This, in turn, creates uncertainties that are propagated in the system and reflected
546 on the final output (i.e. DT).

547 **Figure 9.** Downtime evaluation for a) Power network and b) Telecommunication system for Scenario 1

548 **Figure 10.** Downtime evaluation for a) Power network and b) Telecommunication system for Scenario 2

549 **Figure 11.** Downtime evaluation for a) Power network and b) Telecommunication system for Scenario 3

550 **6. Conclusion**

551 The importance of resilience in the context of managing infrastructure systems is indispensable. Critical
552 infrastructures, such as power and telecommunication networks, are coping with different threats ranging from
553 natural to man-made hazards. In this paper, a probabilistic downtime (DT) assessment and prediction
554 framework using the Bayesian Network (BN) is provided as an initial framework for estimating the recovery
555 time of infrastructures, highlighting how sensitivity analysis can help prepare pre-disaster strategies and assign
556 appropriate resources. The methodology combines DT indicators through a BN-based DT assessment
557 framework to have a first estimate of the total recovery time of power and telecommunication infrastructures
558 that are typically damaged after earthquake events. The inclusion of the uncertain parameters that have a high
559 impact on the recovery process and that are tricky to quantify such as *financing planning, availability of the*
560 *human resource, and regulatory and economic uncertainty*, represents one of the strengths of the methodology.
561 The quantification and characterization of the DT factors associated with power and telecommunication
562 failures are often vague and uncertain, due to their qualitative nature rather than quantitative.

563 The BN-based approach used herein is based on the past data and observation of experts and can capture the
564 knowledge uncertainty. The proposed method incorporates intuitive knowledge and engineering experience
565 for evaluating the parameters of the framework and for estimating conditional probabilities. For instance, the

566 conditional probabilities for each node were obtained by combining expert knowledge and past studies. To
567 show the applicability of the model, three scenarios are introduced where data are partially available.
568 Sensitivity analysis is performed to identify critical parameters that contribute to the DT of lifelines and to
569 help decision-makers to pursue the best strategies for downtime reduction. Sensitivity results showed that the
570 input parameters related to the earthquake intensity and the characteristics of the infrastructure had the highest
571 normalized percent contribution towards the DT, i.e. 0.597% and 0.376%. The highly sensitive parameters can
572 be used to determine parameters that require more time and effort to collect data.

573 The graphical interface of BNs makes the methodology a decent tool for decision-makers (e.g. engineers and
574 managers) who may not be experts in probabilistic analysis. It is believed that the proposed approach should
575 help the decision-makers to evaluate the overall repair time and accordingly quantify the priorities of the repair
576 activities. Moreover, the powerful feature of BN for generating different what-if scenarios enables decision-
577 makers to run scenarios and determine the efficient means of reducing the DT.

578 Results from the proposed framework would be useful in supporting decision-makers on learning about the
579 recovery time of their system given a specific seismic event. By setting a desirable state of the DT and getting
580 the parameters that ensure the predefined DT state, decision-makers are allowed to improve the systems'
581 performance through the backward analysis of BN (diagnostic reasoning).

582 The main limitation of the proposed study is that some of the conditional probabilities are knowledge-based.
583 Subjectivity is needed to be included during the model development and analysis, as it is one of the main
584 features of BN for treating missing data with expert judgment. However, different conditional probabilities
585 that are developed based on evidence data, such as historical data and analytical work, can be integrated within
586 the methodology.

587 Further research will focus on the calibration of the BN model by extending the database to include more key
588 parameters in the DT BN system and taking into account different conditional probabilities to get more
589 accurate results. Other lifelines, such as water and gas systems, will also be analyzed considering the
590 interdependency of infrastructure networks since infrastructure systems are not isolated from each other but
591 rely on one another for their functionality. Finally, fuzzy logic could be applied as an alternative inference
592 system to the BN and then compared to the proposed BN approach.

593

594 **CrediT authorship contribution statement**

595 **Melissa De Iuliis:** Writing – original draft, Methodology, Software, Validation. **Omar Kammouh:**
 596 Conceptualization, Supervision, Writing – review & editing. **Gian Paolo Cimellaro:** Supervision,
 597 Conceptualization, Writing – review & editing, Funding acquisition. **Solomon Tesfamariam:** Supervision,
 598 Writing – review & editing.

599

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604 **Appendix A**

605 Number of affected infrastructures and the corresponding total recovery time [16]

Earthquakes	Lifelines affected							
	Power		Water		Gas		Telecom.	
	No.	DT (days)	No.	DT (days)	No.	DT (days)	No.	DT (days)
Loma Prieta	2 (2), (0.5)		10 (14), (4), (3), (1.5), (2), (1), (3), (3), (7), (4)		5 (30), (16), (11), (10), (10)		6 (3), (4), (0.1), (3), (3), (1.5)	
Northridge	3 (3), (0.5), (2)		6 (7), (2), (58), (12), (67), (46)		4 (7), (30), (5), (4)		3 (1), (2), (4)	
Kobe	5 (8), (3), (2), (5), (6)		3 (0.5), (8), (73)		3 (84), (11), (25)		3 (1), (5), (7)	
Niigata	4 (11), (4), (1)		3 (14), (28), (35)		3 (28), (35), (40)		-	
Maule	6 (14), (1), (3), (10), (14)		4 (42), (4), (16), (6)		2 (10), (90)		4 (17), (7), (3), (17)	
Darfield	3 (1), (2), (12)		2 (7), (1)		1 (1)		3 (9), (2), (3)	
Christchurch	3 (14), (0.16)		1 (3)		2 (14), (9)		2 (15), (9)	
Napa	1 (2)		6 (20), (0.9), (0.75), (2.5), (12), (11)		1 (1)		-	
Michoacán	4 (4), (10), (3), (7)		4 (30), (14), (40), (45)		-		1 (160)	
Off-Miyagi	2 (2), (1)		1 (12)		3 (27), (3), (18)		1 (8)	
San Fernando	1 (1)		-		2 (10), (9)		1 (90)	
The Oregon Resil. Plan	1 (135)		1 (14)		1 (30)		1 (30)	

LA Shakeout Scenario	1 (3)	1 (13)	1 (60)	-
Tohoku Japan	7 (45), (3), (8), (2), (2), (4)	8 (4.7), (47), (1), (26), (7), (1), (47), (47)	6 (54), (2), (30), 3 (49), (21), (49) (3.5), (13), (18)	
Niigata	2 (24)	3 (15), (4), (10)	2 (180), (2)	-
Illapel	1 (3)	1 (3)	- -	-
Nisqually	3 (2), (6), (3)	- -	- -	-
Kushiro-oki	1 (1)	3 (6), (3), (5)	2 (22), (3)	-
Hokkaido Toho-oki	1 (1)	3 (9), (3), (5)	- -	-
Sanriku	1 (1)	3 (14), (12), (5)	- -	-
Alaska	3 (2), (0.75), (1)	5 (14), (5), (1), (7), (14)	3 (1), (5), (2), (14)	2 (1), (2)
Luzon	3 (7), (20), (3)	3 (14), (14), (10)	- -	3 (5), (10), (0.4)
El Asnam	- -	1 (14)	- -	-
Tokachi-oki	2 (2)	- -	2 (30), (20)	-
Kanto	1 (7), (5)	1 (42)	2 (180), (60)	1 (13)
Valdivia	1 (5)	1 (50)	- -	-
Nihonkai-chubu	1 (1)	1 (30)	1 (30)	-
Bam	1 (4)	3 (14), (10)	- -	1 (1)
Samara	1 (1)	1 (2)	- -	1 (1)
Arequipa	1 (1)	3 (32), (34)	- -	-
Izmit	1 (10)	2 (50), (29)	1 (1)	1 (10)
Chi-Chi	3 (40), (14), (19)	1 (9)	1 (14)	1 (10)
Alaska 2002	2 (2), (0.5)	10 (14), (4), (3), (1.5), (2), (1), (3), (3), (7), (4)	1 (3)	6 (3), (4), (0.1), (3), (3), (1.5)

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743 Tables

744 **Table 1.** Description of the Exposure infrastructure parameters

Variable	State	Performance measure/Reference
Exposed Infrastructure	Low	Visual inspection/Expert opinion [66]
	High	
Maintenance Degree	Poor	Visual inspection/Expert opinion
	Medium	
	Good	
Served people	Low	< 20% Population
	Medium	20%<Served People<50% Population
	High	> 50% Population
		[49]
Anti-seismic Infrastructure	Yes	Earthquake resistant
	No	Earthquake non-resistant
Service Importance	Low	Visual inspection/Expert opinion
	Medium	
	High	
Priority of intervention	Low	Visual inspection/Expert opinion
	Medium	
	High	
Recovery Type	Easy	Visual inspection/Expert opinion [43]
	Difficult	
	Very Difficult	
Financing Phase	Short	Visual inspection/Expert opinion [43]
	Medium	
	Long	
Procurement Process	Reactive	Major hazards
	Emergency	State of emergency taken off
	Accelerated	Immediate needs [43, 46]
Building Phase	Easy	Visual inspection/Expert opinion [43]
	Difficult	
	Very Difficult	
	Short	

Engineer Evaluation	Medium Long	Visual inspection/Expert opinion [43]
Event Repetition	Once Many	First shock Aftershocks [43]
Seismic Event	Dangerous Very Dangerous Extremely Dangerous	6<M<7 7<M<8 M>8
Finance Planning	Short Medium Long	Visual inspection/Expert opinion [43]
Repair Effort	Short Medium Long	Visual inspection/Expert opinion [43]
Engineering Consolidation	Easy Difficult Very Difficult	Visual inspection/Expert opinion

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746 **Table 2.** Description of the Earthquake intensity parameter

Variable	State	Performance measure
Epicentral distance	Close	
	Far	Visual inspection/Expert opinion
	Very far	
Earthquake magnitude	Strong	M 6-6.9
	Major	M 7-7.9
	Severe	M 8-8.9
	Violent	M 9-9.9
Earthquake Intensity	Weak	MMI-MMIII
	Major	MMIV-MMVI
	Severe	MMVII-MMX
	Violent	MM>MMX

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748 **Table 3.** Description of the Availability HR variables

Variable	State	Performance measure	Reference
Availability HR	Low	Expert opinion	[66]
	High		
Other Emergencies	Yes	Expert opinion	
	No		
Planning Indicator	Bad	Inadequate and inactive	[48] [67]
	Good	Inadequate or inactive	
	Excellent	Adequate and active	
Impacted Area	Small	Visual inspection/Expert opinion	[67]
	Medium		

	Large		
	Easy		
Mobility and Access	Medium	Visual inspection/Expert opinion	[67]
	Hard		
	Small	50.000<Population<200.000	[43]
Urban Area	Medium	200.000<Population<500.000	[49]
	Large	Population >= 1.5 million	[67]
	Very bad	90°F or 35°F	
Extreme Weather	Bad	80°F or 32°F	[48]
	Good	68°F	[67]
	Low	<5	
PCGDP	Medium	5<PCGDP<40	[67]
	High	>40	[51]
	Low	< 50.000	
Population	Medium	50.000<Population<500.000	[49]
	High	>= 1.5 million	[67]
	Low	< 0	
Urbanization rate	Medium	0 < Urbanization rate < 3	[67]
	High	> 3	[50]

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751 **Table 4.** Description of the DT parameter

Variable	State	Performance measure
Downtime	Very Low	0 - 4 days
	Low	5 - 10 days
	Medium	11 - 24 days
	High	25 - 40 days
	Very High	41 days and more

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753 **Table 5.** Downtime data and corresponding frequencies for Power and Telecommunication networks with EM 6-6.9, 7-7.9, 8-8.9, and
754 9-9.9

Power	DT (days)	0.16	0.5	1	2	3	4	5	6	8	11	14	
	Freq.	1	2	2	4	3	2	1	2	1	1	1	
Telecommunication	DT (days)	0.1	1	1.5	2	3	4	5	7	9	15	90	
	Freq.	1	3	1	1	3	2	1	1	1	1	1	
Power	DT (days)	0.5	1	2	3	7	10	12	14	19	20	24	40
	Freq.	1	6	3	2	1	1	1	1	1	1	1	1
Telecommunication	DT (days)	0.1	0.4	1	2	3	4	5	8	9	10		
	Freq.	1	1	1	1	4	1	1	1	1	3		

Power	DT (days)	1	2	3	4	7	10	14	
	Freq.	3	1	3	1	1	2	2	
Telecommunication	DT (days)	3	7	17	160				
	Freq.	1	1	2	1				
Power	DT (days)	0.75	1	2	4	5	8	45	135
	Freq.	1	1	3	1	1	1	1	1
Telecommunication	DT (days)	1	21	30	49				
	Freq.	1	2	1	2				

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Table 6. Kolmogorov- Smirnov goodness-of-fit test for Power and Telecommunication infrastructures for EM6-6.9

Theoretical distribution	Power network for EM = 6-6.9		Telecommunication network for EM = 6-6.9	
	D_n	$D_n^{\alpha} (\alpha = 0.05, n = 5)$	D_n	$D_n^{\alpha} (\alpha = 0.05, n = 3)$
Gamma distribution	0.127	0.565	0.127	0.708
Exponential distribution	0.148		0.204	
Lognormal distribution	0.218		0.182	

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Table 7. Chi-square goodness-of-fit test for Power and Telecommunication infrastructures with EM6-6.9

Theoretical distribution	Power network for EM = 6-6.9			Telecommunication network for EM = 6-6.9		
	Chi-square χ^2_f $f = k-1$	$C_{1-\alpha,f} (\alpha = 0.05)$		Chi-square χ^2_f $f = k-1$	$C_{1-\alpha,f} (\alpha = 0.05)$	
Gamma distribution	7.12	3	7.81	7.58	5	11.07
Exponential distribution	13.70	2	5.99	7.52	4	9.48
Lognormal distribution	13.58	3	7.81	7.55	5	11.07

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Table 8. Gamma distribution parameters for Power and Telecommunication systems for the four earthquake magnitude ranges

Power system					Telecommunication system				
Parameters	1	2	3	4	Parameters	1	2	3	4
α	0.955	1.424	0.925	0.813	α	0.973	0.317	0.753	1.115
β	4.541	2.777	6.45	18.69	β	10.26	72.06	12.85	44.80

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766 **Table 9.** Downtime probabilities of the power and telecommunication systems given four seismic intensities

Lifeline	Time Span	Weak	Strong	Severe	Violent
Power System	0-4	62%	52%	53%	41%
	5-10	32%	31%	34%	23%
	11-24	5%	15%	13%	23%
	25-40	0%	1%	1%	9%
	40+	0%	0%	0%	3%
Telecommunication System	0-4	43%	10%	25%	9%
	5-10	24%	43%	13%	15%
	11-24	22%	44%	17%	28%
	25-40	8%	4%	12%	20%
	40+	3%	0%	9%	14%

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776 **Table 10.** Conditional Probability Table (CPT) for the downtime variable of the power and telecommunication infrastructures

Infrastructure Type	Earthquake Intensity	Exposed Infrastructure	Av. HR	Very Low	Low	Medium	High	Very High
Power	Weak	High	High	0,62394	0,32123	0,05448	0,00037	0,0000015
Power	Weak	High	Low	0,62390	0,32119	0,05452	0,00044	0,0000015
Power	Weak	Low	High	0,62387	0,32100	0,05453	0,00047	0,00009
Power	Weak	Low	Low	0,62374	0,32080	0,05454	0,00075	0,00019
Power	Strong	High	High	0,52078	0,31280	0,15198	0,01365	0,00081
Power	Strong	High	Low	0,52070	0,31250	0,15214	0,01376	0,00090
Power	Strong	Low	High	0,52065	0,31245	0,15216	0,01379	0,00091
Power	Strong	Low	Low	0,52064	0,31230	0,15151	0,01459	0,00100
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Telecommunication	Weak	High	High	0,43050	0,24320	0,22050	0,07790	0,02790
Telecommunication	Weak	High	Low	0,43000	0,24300	0,22100	0,07800	0,02800
Telecommunication	Weak	Low	High	0,42990	0,24290	0,22150	0,07790	0,02782
Telecommunication	Weak	Low	Low	0,42989	0,24278	0,22155	0,07790	0,02789
Telecommunication	Strong	High	High	0,09823	0,42665	0,43950	0,03510	0,00050
Telecommunication	Strong	High	Low	0,09810	0,42549	0,43981	0,03560	0,00098
Telecommunication	Strong	Low	High	0,09780	0,42544	0,43990	0,03570	0,00111
Telecommunication	Strong	Low	Low	0,09500	0,42540	0,44150	0,03630	0,00180
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779 **Table 11.** Sensitivity analysis for the *Downtime* variable due to a finding at another node (only influential variables are listed)

Node	Variance reduction	Percent contribution
Earthquake intensity	0.895	0.574
Infrastructure type	0.8865	0.569
Recovery type	0.06672	0.0428
Epicentral distance	0.05101	0.0327
Earthquake magnitude	0.02184	0.0014

Planning indicator 3.189e-05 2.05e-05

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Table 12. Inference analysis results for the *Downtime* variable

Node	State
Epicentral Distance	Very Far
Earthquake Intensity	Weak
Recovery Type	Easy
Infrastructure Type	Power/Telecommunication
Downtime	14.7 ± 13/ 19 ± 12
Epicentral Distance	Close
Earthquake Intensity	Violent
Recovery Type	Very Difficult
Infrastructure Type	Power/Telecommunication
Downtime	16.8 ± 12/ 20.2 ± 10

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Table 13. Input data used to assess the downtime of the power lifeline

Variables	Scenario 1	Scenario 2	Scenario 3
Anti-seismic Infrastructure	Yes	Yes	No
Assessment of the damage	Short	Medium	-
Procurement process	Emergency	-	-
Epicentral distance	Close	Far	Close
Earthquake magnitude	Strong	Major	Severe
Mobility and Access	Easy	Medium	-
Engineering Consolidation	Difficult	-	-
Event Repetition	Once	Many	Once
Extreme weather	Good	Bad	Very Bad
Finance Planning	Medium	Short	-
Infrastructure type	Power	Power	Power
Maintenance degree	Good	Medium	Poor
Other Emergencies	No	Yes	Yes
Per Capita GDP	High	Medium	Low
Planning Indicator	Excellent	Good	Bad
Population	High	High	Medium
Repair Effort	Difficult	-	-

Served People	High	Medium	High
Service Importance	High	High	Medium
Structural inspection	Short	Medium	-
Urbanization	High	Medium	Medium

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Table 14. Input data used to assess the downtime of the telecommunication lifeline

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Variables	Scenario 1	Scenario 2	Scenario 3
Anti-seismic Infrastructure	Yes	Yes	No
Assessment of the damage	Short	Medium	-
Procurement process	Emergency	-	-
Epicentral distance	Close	Far	Close
Earthquake magnitude	Strong	Major	Severe
Mobility and Access	Easy	Medium	-
Engineering Consolidation	Difficult	-	-
Event Repetition	Once	Many	Once
Extreme weather	Good	Bad	Very Bad
Finance Planning	Medium	Short	-
Infrastructure type	Telec.	Telec.	Telec.
Maintenance degree	Good	Medium	Poor
Other Emergencies	No	Yes	Yes
Per Capita GDP	High	Medium	Low
Planning Indicator	Excellent	Good	Bad
Population	High	High	Medium
Repair Effort	Difficult	-	-
Served People	High	Medium	High
Service Importance	High	High	Medium
Structural inspection	Short	Medium	-
Urbanization	High	Medium	Medium

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