POLITECNICO DI TORINO

Department of Structural, Building and Geotechnical Engineering

Master of Science in Civil Engineering

Structures

Master Thesis

The Resilience of Critical Infrastructures

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I would like to dedicate my thesis to my dad, Sebastiano Teresio, Professor at Polytechnic University of Turin, who has always been my inspiring role model in the engineering field. Big thanks should go to my parents and my sister, for their endless encouragement and support during my years of studies.

I must say a huge thank you to my dear girlfriend Cecilia for her lovely support and patience, and to her family. I want to thank also my old friends (Paola, Maria Caterina, Danila and Gianluca) for being always present in my life. There are a number of friends at Polytechnic University of Turin I would like to say a big thank you for their constant support and for sharing the happiest and the most meaningful time of my academic life (Alessandro, Daniele, Sabino, Ilmi and Giulio).

I must thank you my supervisor, Prof. Gian Paolo Cimellaro, for his inspirations and priceless advice. My gratitude also goes out to my advisors, Prof. Marco Domaneschi and Prof. Andrea Mazza, who kindly guided me throughout my studies.

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1 INTRODUCTION

Resilience term derives from the Latin word "resilio", which means to jump back.

Recent natural disasters led to questioning how communities can recover, and the most consolidated approach is to study the interdependence between different networks.

At Politecnico di Torino an innovative approach in the resilience field is proposed by Professor G.P. Cimellaro’s research group and it is called "Ideal City". Ideal City is a resilience-based designed community freely inspired by the City of Turin. All the critical infrastructures are modelled as independent layers and then the multiple cascading effects between them are analysed.

This thesis starts with a brief overview of the transportation network and its main aspects, proposing an Agent-Based Model (ABM) to study the people behaviour inside a city. Representing the standard situation before the occurring of an earthquake, the transportation network of the city is converted in the Python language and the behaviour of agents moving on the roads is defined. This model works as a traffic model thanks to the storage of hundreds of data from Google about the real traffic in Turin, reproducing properly the movements of the cars during working days and weekends.

This ABM is the starting point of an evacuation model where agents move trying to reach safe recovery areas. The model was developed during a research period at the University of California, Berkeley under the supervision of Professor Kenichi Soga, and other colleagues of mine are deepening this topic.

The main part of this study is related to the distribution power network. A new index to assess the grid performance is introduced and then it is validated by comparing it with two parameters already present in literature and testing it on an urban case study.

Real data to model the Ideal City power network are not available because electric companies do not want to share sensitive data for external researches. In addition, the classical operation is to improve the single substations, and not to have a comprehensive analysis of the network weaknesses. For this reason, the approach presented is innovative and therefore two innovative methodologies are proposed and implemented to realize the entire grid. For the sake of clarity, this modelling part has been supervised by Professor A. Mazza from the Department of Energy of the Politecnico di Torino and the results are comparable with the few data released by IRETI, the Turin electricity distribution authority.

In the end, the resilience of the network is calculated using a real disaster, the 1979 Norcia Earthquake. Collapsed buildings and areas without electricity supply are shown.

To sum up, the purpose of this work is to analyse the main critical city infrastructures to develop a tool useful for city planners and managers to enhance the communities' resilience.

2 An Agent-Based Model for the Transportation Network

2.1 Overview: the traffic problem

In the recent years natural disasters are playing a crucial role for the development and the prosperity of the communities around the world. The cities are experiencing a heavily overcrowdings, due to an increased tendency of the population of leaving the rural areas for the more preferred urban ones.

On one hand, the lack of proper tools adopted by urban planners and on the other, the tremendous amount of deaths due to catastrophes, brought our team to develop this software. This is intended to be the beginning and the inspiration for further development, and still not the solution to this problem. The traffic problem is not just simulating the traffic itself during a normal working day but could be the simulation during a disaster of the behaviour of the cars, but not only, also the people during an evacuation. Many applications can derive from this work and many other can be thought by the reader. This approach has been inspired by a similar work made by University of Cambridge on the city of London (Casey 2017, Soga 2017).

Future developments are leading our team to study also the streets and roads crowding during the traffic simulation, that can be applied also during a city evacuation.

This work was performed during my period as Visiting Student Research at University of California, Berkeley, collaborating with the City-scale modelling research group of Professor Kenichi Soga.

The results here presented were achieved with Bingyu Zhao (PhD student, University of Cambridge) and with a colleague from the Professor Cimellaro's research group, Alberto Annichini (Master student, Politecnico di Torino), with whom I wrote this chapter.

2.2 Method description

This paragraph is intended to give the key elements for understanding the methodology behind the development of an Agent-Based Model for traffic simulation with data taken from Google Maps. This straight forward structure is intentionally created for clarity, but for a more complete and wider understanding, the following section (Annexes) is suggested to read. That part includes concepts explanation and scripts collection, that will help the reader to better understand the traffic problem and reproduce the proposed solution.

The procedure can be summarized in eight different steps:

1. Target area and map data collection;
2. Harvesting and storing traffic data;
3. Processing data and compute the average;
4. Imputing;
5. Harvested and imputed data of multiple networks;
6. Graph analytics.
7. igraph package and the algorithms
8. Visualization

<u>Target area and map data collection</u>

The first step consists in collecting data from Open Street Maps (OSM) about a predefined region or city. This will be the target area of the simulation.

Information needed for the creation of the network in the Python environment are the following coordinates related to:

- The beginning and the ending of each street. These are actually given as coordinates of straight broken lines that compose every road of the selected area. In the Python code this can be referred to "list_of_links" (i.e. the coordinate collection of all the links)
- Intersections of all the streets. In Python this is referred to "list_of_nodes" (i.e. the coordinate collection of all the nodes)

All the previously mentioned data referred to the topology of the selected network can be downloaded from OSM in the Geojson format, thanks to a script. This will be the input of the function included in the package Python-igraph for the graph creation related to the network.

For performing this step, the Script “From OSM to Python” (Annex 1) should be executed.

Moreover, in case of target area not present in OSM or for a completely customized map, another Script called “From DXF to Python” (Annex 2) can be executed, instead of the previous one. This code allows the user to import a .dxf file and convert it into a Geojson format.

Harvesting and storing traffic data

The second step consists in collecting traffic data from Google Maps thanks to the Amazon Virtual Machine Elastic Compute Cloud (EC2) and uploading them on Amazon Simple Storage Service (S3).

The data useful for the creation of the Agent-Based are the travelling time and the length of each road (i.e. list_of_links) in the selected city (i.e. graph) or area around the world.

The object of the Google inquiry is a single link given from the OSM “list_of_links”, setting the origin and the destination respectively as the coordinates of the beginning and the end of each link. These are requested in a random way and the outputs are in two different formats:

- Format 1: a photo that can be visualized on the browser. This is just a picture of the path requested with any coordinates or any other information easily processable.
- Format 2: a .txt and shows the travelling time and the length needed from the origin to the destination. This file can be transformed into .json file (or also .xml) thanks to a script.

The second type is the one that will be used for the simulation.

Unfortunately, there are some drawbacks regarding this step:

- The free traffic data comes with a private Google account that has a daily allowance of 2,500 requests. For this reason, it is necessary to set the virtual machine (EC2) for performing inquiries at different hours (e.g. 100 inquiries every hour – one-hour time step) every day and store them in the cloud service (S3). Moreover, the data that can be collected are referred just at the time in which we the request is sent, and it is not possible to refer to historical data. Lastly, the frequency of sampling can be defined based on:
    - the number of links of the target system;
    - which week or weekend days the data are requested;

In this way it is possible to have for free the data, otherwise it should be more reasonable to go with a business account or directly contact Google Maps.

- The inquiry concerns the coordinates that belong just to a single link and not to a set of links. It will be more efficient requesting the travelling time for much longer paths (set of links – A'B'), but Google is not always providing the travelling time of those specified links, but the shortest way in terms of travelling time between the two coordinates. The output could be very different of what expected and for this reason the request is just a single link (AB). Unfortunately, also at this point another problem can rise. The inquiry of the single link can again give back an alternative path more convenient in terms of travelling time (ACDB). For this reason, a script in the code is written for checking the length of the link requested and the length of the path given as output. If their difference is higher than 10% means that Google returned a different way and not what asked, and the result must be considered wrong, and so deleted. Statistically just 80% of all the inquiries are successful.

Figure 2-1 Single link AB, alternative path ACDB and the set of links A'B'

For performing this step, the Script "Harvesting Google Data" (Annex 3) should be executed.

Processing data and compute the average

Processing data means merging all the files collected in many days. A good assumption could be considering that the biggest difference about traffic behaviour will be during weekdays (Monday-Friday) and weekend days (Saturday-Sunday). If data are taken at every hour of the day, there will be 24 graphs each day. It is now possible to merge them based on the consideration made before, there will be 24 graphs for weekdays and 24 for weekend days.

Before the merge, if some information about the travelling time of two identical links are taken twice, there is a piece of code that is computing the average of both. It is possible to have duplicate file because the process of requesting the travelling time is random. It consists of a casual selection of 100 links every hour (if the time step is one hour) from the "list_of_links" and if by chance that link was already requested, the new travelling time is the arithmetic average of the 2 times.

At this point, the overall set of graphs to be processed are in total 48 graphs.

Imputing

This step can be skipped in case of Google business account or in case of no restriction in terms of time spent in harvesting data from Google Maps (until harvested 100% of the data in Step 2).

Otherwise, it is necessary to impute the data to all the close streets in term of functional class (i.e. street type – residential, high way etc). It is reasonable to assume that close streets with same functional class have the same speed – in case of traffic the cars will be redistributed in proximal streets. If the traveling time of a particular link and the length is known, it is possible to compute the speed with the easy relationship that comes from the Physics. When the calculation is done and thanks to a Python script, close streets (links) with same functional class will have assigned same speed. Using the reverse relationship and knowing the length of the near links, it is possible to assigns to each of them the travelling time.

Having just 10% of all the data needed are enough for imputing all the rest. More data were harvested, more precise the imputing and the simulation will be.

Harvested and imputed data of multiple networks

After the third and fourth step there will be 48 networks representative of the target area traffic with all the real data and the one imputed. At this point is possible to procced with all the graphs computations at step 6.

Graph analytics

After having selected one graph to proceed, many different computations can be performed, like:

- Shortest path
- Centrality (nodes connectivity)
- And others

The one that most interests the traffic is the first: the shortest path computation. This problem can be analysed in many ways, the most common are:

- Single-pair shortest path problem (SPSP)
- Single-Source Shortest Path problem (SSSP)
- Single-Destination Shortest Path problem (SDSP)
- All-Pairs Shortest Path problem (APSP)

Each Agent in the traffic has an origin and a destination that would like to reach in the lowest time possible. Transposing everything in the graph theory, this is problem that can be defined as finding the shortest path between two vertices (or nodes – origin and destination) minimizing the sum of the weights (travelling time) of each edge that are composing the path itself. The SPSP problem is the most suitable one for this purpose.

<u>igraph package and the algorithms</u>

After having defined which is the problem leading the traffic analysis (SPSP), it is possible to start the implementation of the code. The class Graph inside the package Python-igraph, has the function *shortest_paths_dijkstra(source=None, target=None, weights=None, mode =OUT) (Igraph-library Team 2014)*, where, for given vertices in a graph, the script impute the lengths of the shortest path. The parameters to be included are the source, the target, the weights and the mode(Igraph-library Team 2014).

Thanks to this function, is possible now to calculate as many paths are needed for the simulation, knowing the origins and the destinations of the agents. A stochastic approach can be also adopted.

Visualization

In this final step, it will be described how to visualize the entire network with the agents moving on it.

For making this possible, an important application is DeckGL (the visualizer) that allows to see the movement of the agents on the graph created with igraph. For a more realist view of the all simulation, MapBox is also introduced. Thanks to this software, all the graph will be located on the real map of the selected target area, showing in background the details, like mountains, landmarks, airports and many other things.

2.3 Case study: Ideal City

As a case study, the traffic problem has been applied to Ideal City, using the road data of the metropolitan city of Turin, Italy.

The figure 2-2 is showing the target area. In black there are the roads that the agents can decide to drive. They look like streets, but actually it is a graph in Python-igraph. In grey and white there is the background created with MapBox.

Figure 2-2 Turin network visualized on DeckGL and MapBox as background

Figure 2-3 Detail of Turin Network, Politecnico di Torino neighbourhoods

The red and blue colours in Figure 2-4 are just randomly assigned to different agents, for making the visualization clear.

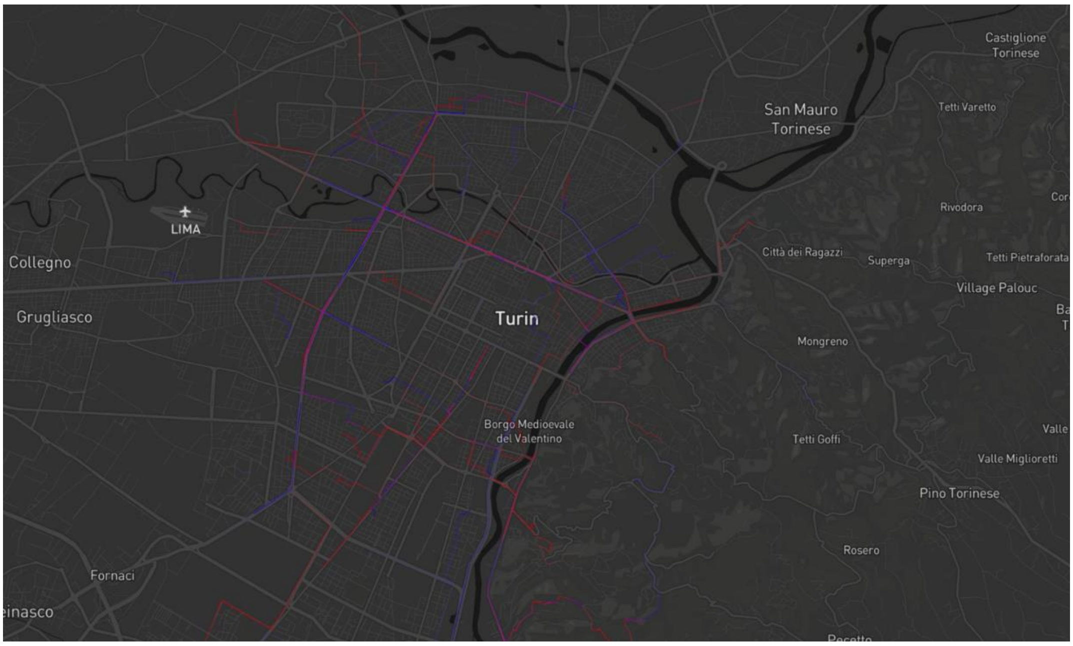


Figure 2-4 Visualization of 80 moving agents in the Turin Network

2.4 Annexes

Annex 1 "From OSM to Python"

1. Open cmd
2. Create folder turin: $ mkdir turin
3. Clone the repo turin_roadnetwork: $ git clone https://github.com/silviosordo/turin_roadnetwork.git
4. Request data from OSM: $ echo "data=[out:json][bbox:45.0080,7.6017,45.1326,7.7336];way[highway];(._; >;);out;" > query_turin.osm
5. Download data from OSM: $ curl -o target_turin.osm -X POST -d @query_turin.osm http://overpass-api.de/api/interpreter
6. Install python3, there are two ways:
   a. Download from the website https://www.python.org/downloads/ and add to the cmd path
   b. $ sudo apt-get update

      $ sudo apt-get install python3.6
7. Install pip3:$ sudo apt-get install python3-pip
8. Install igraph: $ pip3 install python-igraph
9. Run the .py file to convert data from OSM to geojson that is the correct format to visualize data with the application DeckGL: $ python3 osm2geojson_bing.py
10. To visualize data, we need to have the .json file on a web storage. Start going on AWS Amazon Web Services and creating a new Storage S3 bucket

i. AWS home, Services, S3
ii. Create Bucket, choose a “bucketname”, and choose “US East (N.Virginia)” as region because before in aws configure we decided region = us-east-1).
iii. Click three times on Next, then Create Bucket
iv. Inside this bucket Create a folder, choose “bucketfoldername” as name. Leave “None” as default encryption setting, then Save
v. Inside the bucket modify Permissions → CORS Configurations and set them like that (copy paste and then click on Save)

```
<!-- Sample policy -->
<CORSConfiguration>
        <CORSRule>
                <AllowedOrigin>*</AllowedOrigin>
                <AllowedMethod>GET</AllowedMethod>

<MaxAgeSeconds>3000</MaxAgeSeconds>

<AllowedHeader>Authorization</AllowedHeader>
        </CORSRule>
</CORSConfiguration>
```

11. Go back to the terminal, go to the folder Case_geojson_turin: $ cd Case_geojson_turin
12. Modify the web address of the .json file inside the app.js file:
    a. $ nano app.js

b. At line 14 paste the DATA URL of the .json file inside the S3 bucket, example: 'https://s3-us-west-2.amazonaws.com/turin-roadnetwork/turin_full.json'

c. To save and exit: crtl+X, yes, and enter

13. Install the Javascript client yarn: $ yarn
14. Set the Mapbox key to add the background to the map: $ export MapboxAccessToken=pk.eyJ1IjoiYWxiZXJ0b2FubmljaGluaSIsImEiOiJjamYxbjBwYjgxNTFhMnhvaGRwa25sOGI0In0.i5f6AyeXhZy-34U2KAXn1A

    (be careful, no spaces between ‘MapboxAccessToken’, the equals sign ‘=’ and the name of the key
15. Start the Javascript client npm: $ npm start
16. Your browser (google chrome is preferable) will be automatically redirect to the URL with the map of Turin with the correct geographically background

Annex 2 "From DXF to Python"

1. Open cmd
2. Create folder turin: $ mkdir turin
3. Clone the repo turin_roadnetwork: $ git clone https://github.com/silviosordo/turin_roadnetwork.git
4. Upload inside the "turin" folder the DXF file of the desired map
5. Be sure that the name of the DXF file is correctly set inside the .py file "ogr_test.py" (line 28). We will use this script to convert data from DXF to geojson that is the correct format to visualize data with the application DeckGL.
6. Install python3, there are two ways:
    a. Download from the website https://www.python.org/downloads/ and add to the cmd path
    b. $ sudo apt-get update

        $ sudo apt-get install python3.6
7. Install pip3:$ sudo apt-get install python3-pip
8. Install igraph: $ pip3 install python-igraph
9. Run the .py file to have to correct geojson output: $ python3 ogr_test.py
10. To visualize data, we need to have the .json file on a web storage. Start going on AWS Amazon Web Services and creating a new Storage S3 bucket
    i. AWS home, Services, S3
    ii. Create Bucket, choose a "bucketname", and choose "US East (N.Virginia)" as region because before in aws configure we decided region = us-east-1).

iii. Click three times on Next, then Create Bucket
iv. Inside this bucket Create a folder, choose "bucketfoldername" as name. Leave "None" as default encryption setting, then Save
v. Inside the bucket modify Permissions → CORS Configurations and set them like that (copy paste and then click on Save)

```
<!-- Sample policy -->
<CORSConfiguration>
        <CORSRule>
                <AllowedOrigin>*</AllowedOrigin>
                <AllowedMethod>GET</AllowedMethod>

<MaxAgeSeconds>3000</MaxAgeSeconds>

<AllowedHeader>Authorization</AllowedHeader>
        </CORSRule>
</CORSConfiguration>
```

11. Go back to the terminal, go to the folder Case_geojson_turin: $ cd Case_geojson_turin
12. Modify the web address of the .json file inside the app.js file:
    a. $ nano app.js
    b. At line 14 paste the DATA URL of the .json file inside the S3 bucket, example: 'https://s3-us-west-2.amazonaws.com/turin-roadnetwork/turin.json'
    d. To save and exit: crtl+X, yes, and enter
13. Install the Javascript client yarn: $ yarn

14. Set the Mapbox key to add the background to the map: $ export MapboxAccessToken=pk.eyJ1IjoiYWxiZXJ0b2FubljaGluaSIsImEiOiJjamYxbjBwYjgxNTFhMnhvaGRwa25sOGI0In0.i5f6AyeXhZy-34U2KAXn1A

    (be careful, no spaces between ‘MapboxAccessToken’, the equals sign ‘=’ and the name of the key
15. Start the Javascript client npm: $ npm start
16. Your browser (google chrome is preferable) will be automatically redirect to the URL with the map of Turin with the correct geographically background

Annex 3 "Harvesting Google Data"

1. Create a GitHub account with your educational email. https://github.com/
2. Create an account on Amazon Web Services (AWS) - Cloud Computing Services https://aws.amazon.com/?nc2=h_lg
    i. Creating a Personal account
    ii. Filling the form with your information
    iii. Add a credit/debit card because in this service you can purchase some features but all the options we will use are free
    iv. Confirm your account replying to the phone call (tell the code they provide after the registration)
    v. It takes up to one day (at least 2-3 hours) to have the full access to the console
3. Run an EC2 virtual machine ("Launch a virtual machine")
    i. Step 1 Choose an Amazon Machine Image (AMI): Ubuntu Server 16.04 LTS (HVM), SSD Volume Type - ami-916f59f4 (then click on Next)
    ii. Step 2 Choose an Instance Type: General Purpose t2 micro Free tier eligible (then click on Next)
    iii. Step 3 Configure Instance Details, Step 4 Add Storage and Step 5 Add Tags: default settings are ok (then click on Next)
    iv. Step 6 Configure Security Group: modify the default rule, choosing "my IP" as Source (then click on Review and Launch)
    v. Step 7 Review Instance Launch: default settings are ok (then click on Launch)
    vi. Select and existing key pair or create a new key pair: choose Create a new key pair, decide freely the Key pair name and then Download key pair (then click on Launch Instance)
    vii. Launch status: your instances are now launching and click on View Instances
4. Download the free version of MobaXterm to have a user interface of AWS.

https://mobaxterm.mobatek.net/

All the command lines will be insert in this software (only for Windows users, for MacOS users you can use your terminal) Install the “Portable edition”

5. Start a local terminal and connect to a ubuntu EC2 instance ssh -i path/of/the/key/pair ubuntu@IPv4PublicIP
6. If there are any problems accessing to the EC2 machine for example “ssh permission are too open” try the command: chmod 400 path/of/the/key/pair
7. Install Python modules
   i. sudo apt-get update
   ii. Install pip3: sudo apt-get install python3-pip
   iii. Install python modules: pip3 install numpy pprint (pprint is module for printing better json files)
8. Install and configure Boto 3
   i. Install the latest Boto 3 release via pip: pip3 install boto3
   ii. Go on AWS and click on the menu “yourname” and select “My Security Credentials”, then Access keys (access key ID and secret access key) and click on “Create new access key” and Download Key File
   iii. Come back to MobaXterm
   iv. sudo apt-get install awscli
   v. aws configure
   vi. insert “access key ID” and “secret access key” as in AWS-Security Credentials , “region”= us-east-1 and “output” = json
9. Get the code typing git clone https://github.com/silviosordo/baytraffic_share.git and insert your GitHub credentials
10. (Set the Google key at https://developers.google.com/maps/documentation/directions/get-api-key and doing Get a Key using your Google Account (click on Yes))

11. Set the Google Key at https://developers.google.com/maps/documentation/directions/get-api-key#standard-auth and follow the instruction to “Detailed guide for users of the standard Directions API” , create a new Project and select the project “Distance Matrix API”
12. In the baytraffic_share folder modify the google_key.py file, replacing the text the API key enclosed by the quotation mark and save. nano google_key.py and then crtl+X, yes, and enter
13. OSM Data: prepare and request data from OSM checking the boundary box of Turin, and then
    i. echo "data=[out:json][bbox:45.0080,7.6017,45.1326,7.7336];way[highway];(._;>;);out;" > query_turin.osm
    ii. curl -o target_turin.osm -X POST -d @query_turin.osm http://overpass-api.de/api/interpreter
14. Using the text editor nano to open the file osm_converter.py and
    i. comment #:
        a. line 20: print('example node: ', nodes_dict['26117861'])
        b. line 47: print('example link: ', links_dict['12437582'])
        c. line 48: print('example link: ', links_dict['12437582r'])
        d. line 72: pprint.pprint(links_dict['8915500'])
    ii. modify line 13 from osm_data = json.load(open('target_bay.osm')) to osm_data = json.load(open('target_turin.osm'))
    iii. remove the comment to line 74 and 75
    iv. modify line 74 from with open('data_repo/nodes.json', 'w') as nodes_outfile to with open('data_repo/nodes_turin.json', 'w') as nodes_outfile
    v. modify line 77 from with open('data_repo/tagged_alloneway_links.json', 'w') as links_outfile

to with open('data_repo/tagged_alloneway_links_turin.json', 'w') as links_outfile:

15. Run the python file: python3 osm_converter.py
16. Start now to harvest data. Start going on AWS and creating a new Storage S3 bucket
    i. AWS home, Services, S3
    ii. Create Bucket, choose a “bucketname”, and choose “US East (N.Virginia)” as region because before in aws configure we decided region = us-east-1).
    iii. Click three times on Next, then Create Bucket
    iv. Inside this bucket Create a folder, choose “bucketfoldername” as name. Leave “None” as default encryption setting, then Save
17. Go back to MobaXterm and open the related python file: nano data_harvest.py and modify:
    i. number of links = 100
    ii. S3_bucket = “bucketname”
    iii. S3_folder = “bucketfoldername”
    iv. Line 19: from nodes_dict = json.load(open(absolute_path+'/data_repo/nodes.json')) to nodes_dict = json.load(open(absolute_path+'/data_repo/nodes_turin.json'))
    v. Line 20: from links_dict = json.load(open(absolute_path+'/data_repo/tagged_alloneway_links.json')) to links_dict = json.load(open(absolute_path+'/data_repo/tagged_alloneway_links_turin.json'))
18. Run the python file: python3 data_harvest.py
19. Check now if in the AWS bucket there are the expected data in the chosen folder (refreshing the page directly from AWS, no from the browser)
20. To set the automatic harvesting of data type:

i. Check the path of your python3 (type which python3 probably it is /usr/bin/python3)

ii. In that case, type: env EDITOR=nano crontab -e

iii. Add the line: 0 * * * * /usr/bin/python3 /home/ubuntu/baytraffic_share/data_harvest.py (in this way every hour the code will automatically download the data)

iv. Type: crontab -l to check that all added commands are correct

21. To check if there are issues in the data harvesting:

    i. Install the service typing: sudo apt install mailutils (choose Local only as General type of mail configuration, then OK, then press again OK)

    ii. Check the service typing: sudo mail

22. To exit from the EC2 machine type logout

3 Resilience in Distribution Power Networks

3.1 Background

3.1.1 A Power System: how it is made

The Power Systems backbone is composed of four main sectors: generation, transmission, distribution and utilization. This composition is shown in Figure 3-1 (Salman 2016)

Electricity is generated starting from sources of primary energy, such as hydro, wind, fossil fuels and nuclear.

Usually electric power is produced at a voltage level between 11 and 30 kV and so it is not high enough to be transported over long distances. For this purpose, generation substations are used to step up the voltage to the transmission network.

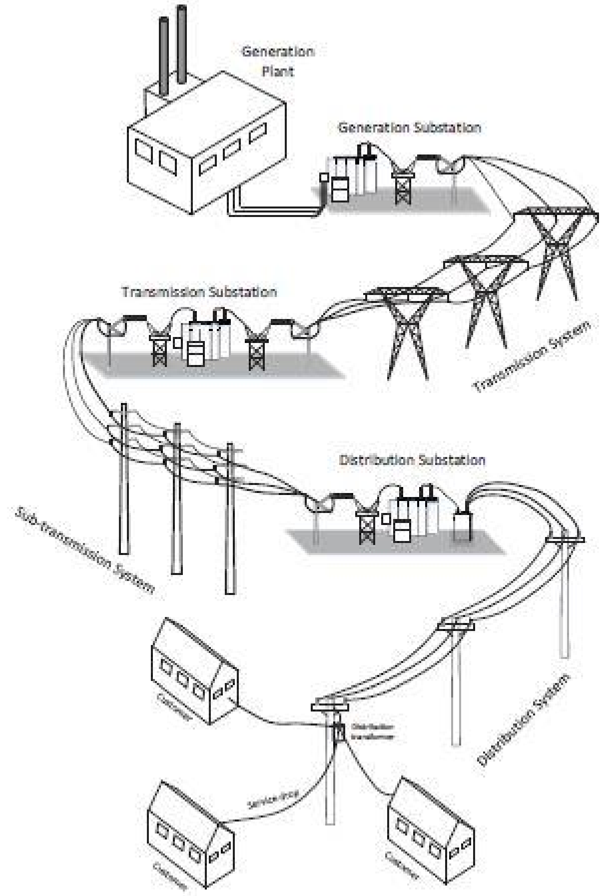


Figure 3-1 Scheme of an Electric Power Network

The transmission network is the part of the system responsible to deliver power through long distances. For that reason, the voltage level is high and, e.g. in US it is in range between 69 kV and 1100 kV (Brown 2008). Near built-up areas electricity sub-transmission systems are set up to step down electricity in such a way to be delivered to multiple distribution networks (Kassakian 2011). The key element of the transmission grid is the redundancy in the mesh because it is designed to provide multiple paths to the connect one substation to another. Networks resilience and reliability are so granted (Brown 2008).

3.1.2 Recent Biggest Blackouts

Italy is a country often affected by blackouts of different magnitude. In September 2003 a huge power loss affected all the Italian citizen (Cormier 2015). It happened in the middle of the night and it was caused by a fault in the Swiss power system that caused the overloading of two lines situated along the Italian border. In particular, it had a big effect on the train transportation, because 110 trains with thousands of passengers were stranded.

This is a clear example of how the interconnection between the Italian network and other European ones could cause cascading effects. That type of failure happened again three years later, in November 2006, when in north-western Germany a power company manually switched off a high-voltage line across the River Ems to let a cruise ship pass. This operation caused an overload that affected around 15 million European inhabitants in Italy, France, Austria, Belgium and Spain.

Unfortunately, this is not only a European problem, but situations like that are common in the electricity supply history. In 1965 a faulty relay in a substation in Ontario caused a domino effect that led to the second biggest d power failure in U.S. (Burke 1985).

This blackout affected 30 million of people in New Jersey, Connecticut, Massachusetts, Rhode Island, New Hampshire, Vermont, Quebec, and Ontario. To give an idea of the situation, that power failure happened during the New York rush hour blocking 800,000 people in the subway. With a prompt action from the American power companies and the government, in 13 hours the grid was partially restored.

The biggest in the U.S. history happens several years later, in August 2003, when first a failure of a high-voltage power line in Ohio and then some mistakes by repairs squads led to a blackout that affected 55 million of people (CBC News Online April 21, 2010). In that case, only after two days, the electricity was partially resupplied and a special commission to analyse these failures was instituted.

For sake of clarity, the biggest failure didn't happen in the American or European continent, but it happened in Asia and more than half a billion people were interested. The real causes are still unknown, but probably an overload or human error caused a blackout that affected 620 million people and 22 states (Deccan Herald 2012).

In addition to that, also extreme events cause every year big power outages. In 2005 the Katrina hurricane caused a big blackout in the South-East part of United States. 2.6 million people were disabled at that time.

Figure 3-2 Hurricane Katrina effects on power networks (Larino 2015)

Every year, especially in the summer period, California is affected by wildfires. They could be the trigger or the consequence of a power failure. Sometimes the failures of poles or lines are caused by an arson, sometimes vegetation is electrified by a line hit by a fallen tree. Power network failures caused four of the historical largest fires in California (Krieger 2017).

Figure 3-3 Fallen pole in Santa Rosa, California (Krieger 2017)

There is also a strict relation between blackouts and earthquake. A clear example of that was the 2011 Christchurch earthquake in New Zealand. In that case, the sub-transmission and the distribution network was destroyed and 80% of the consumers were disabled. The grid was mostly restored in five days, but some central areas were out of power for more than a month.

Figure 3-4 Overhead distribution lines damaged during the Christchurch earthquake (Giovinazzi 2011)

These are only a few examples of how a blackout could be disruptive in terms of economic losses and issues to the citizen lives. This is the reason this thesis is focused on resilience to extreme events, in particular to earthquakes.

3.1.3 Focus on Distribution Networks

3.1.3.1 Overview

Alternating current Medium Voltage (MV) and Low Voltage (LV) feeders and substations composed the infrastructures to transfer electricity from transmission grid to big industrial plants and to small costumers. (Cataliotti 1983-1999)

Usually, in Italy energy is produced at 10 kV and then it could be used at HV level by big companies (e.g. FCA in Turin has this system), at MV by small plants or it is transformed several times using MV/MV or MV/LV substations (in Italian they are called "cabine secondarie") developing the classical urban LV network.

Typically, feeders could be shunt or in series.

In the first case the voltage is constant, and it is the most common because they have better performances in terms of transmission between the maximum and the minimum load and for the reliability of the grid. It is also simpler to increase the network with new elements.

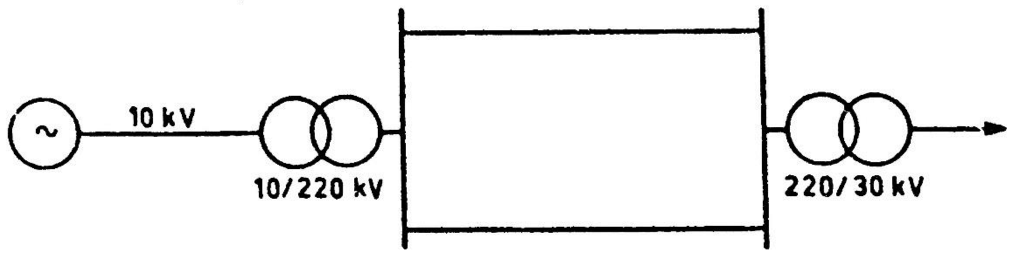


Figure 3-5 Indirect energy supply scheme (Cataliotti 1983-1999)

In the second case the current is constant, and it is rarely used only when few costumers need a high load or when the supply regularity is required by an important function, for example in the street lighting.

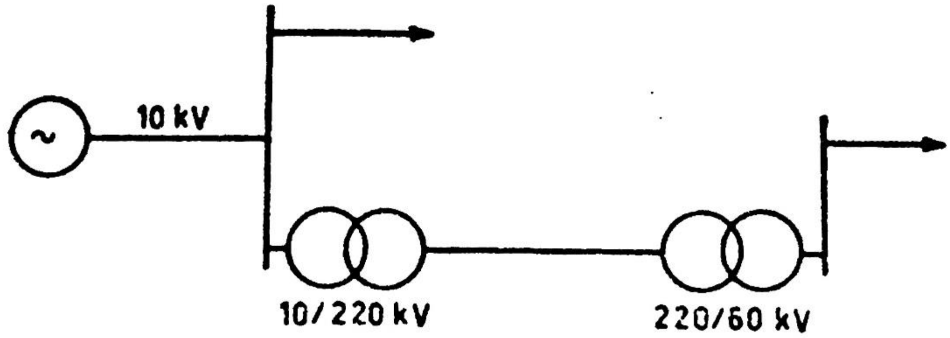


Figure 3-6 Big user HV supply scheme (Cataliotti 1983-1999)

In Italy are now many years that all the distribution LV voltages were standardized to 400 V. For the MV ones CEI codes suggest values like 10, 15, 20 and 30 kV. Usually in medium and large Italian cities a value around 20 kV is used both for MV cabled underground grids of the city centres and for countryside overhead lines. For LV lines generally is taken as reference the 230/400 V value.

3.1.3.2 Network requirements

Generally, it is not possible to use a single type of grid. Loads could change in density and redistribution and so different requirements lead to different schemes.

However, all of them have to respect some conditions (Cataliotti 1983-1999):

- Good electricity supply quality: the frequency constancy, no unbalanced loads and limited differences between nodal voltages and nominal ones.
- Topological flexibility: if loads increase, the network could be easily adapted. This is valid for MV networks but not for LV ones.

3.1.3.3 Load density

In rural or city centres these are the main load density values founded (Cataliotti 1983-1999):

Table 1 Load density in different field of application

Field of application	**Load density [MW/km^2]**
Big cities over 500,000 inhabitants	6 ÷ 10
Big cities from 100,000 to 500,000 inhabitants	3 ÷ 6
Small cities up to 100,000 inhabitants	1 ÷ 3
Small residential communities	1 ÷ 3
Isolated homes with electrical utilities	1 ÷ 2
Rural isolated homes	0,2 ÷ 1

3.1.3.4 MV grid schemes

In this work the focus will be on the MV/LV substations so it is important to define which are the main schemes used in designing MV lines (Cataliotti 1983-1999).

The most used type in big cities is the Ring network.

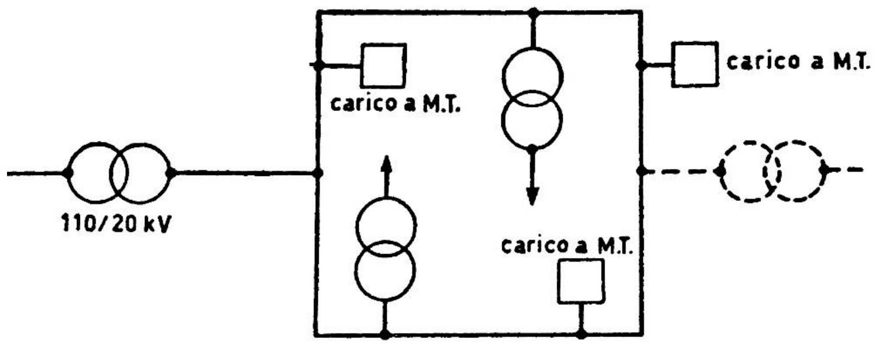


Figure 3-7 Ring scheme (Cataliotti 1983-1999)

There is more than one main substation and it is useful to supply big loads. Failure could be easily cleared and the supply restored disconnecting temporarily the damage part of the grid and loads are more efficiently redistributed.
Usually there are used combined with the radial scheme.

However, it could be possible to find other typologies, maybe used for specific needs:

- Spider network: connections are simply sectioned

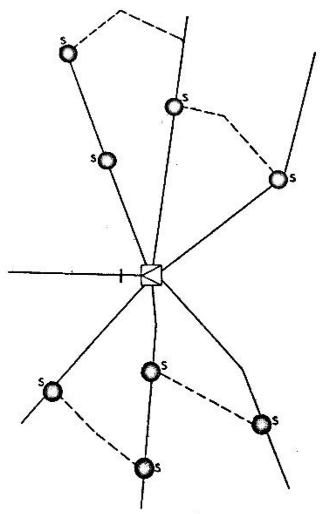


Figure 3-8 Spider scheme (Cataliotti 1983-1999)

- Daisy network: feeders are joined using disconnectors

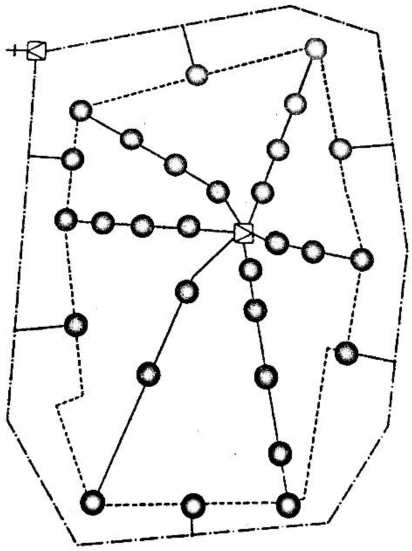


Figure 3-9 Daisy scheme (Cataliotti 1983-1999)

- Multiple rings network: using disconnectors two or more rings are joined when a single ring is not sufficient

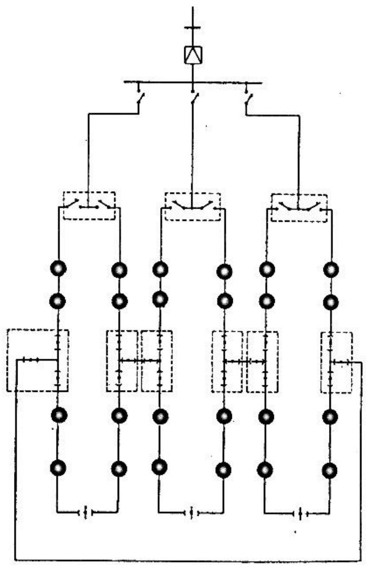


Figure 3-10 Multiple rings scheme (Cataliotti 1983-1999)

- Petal network: two or more rings are supplied by the same HV/MV substation when a single ring is not enough

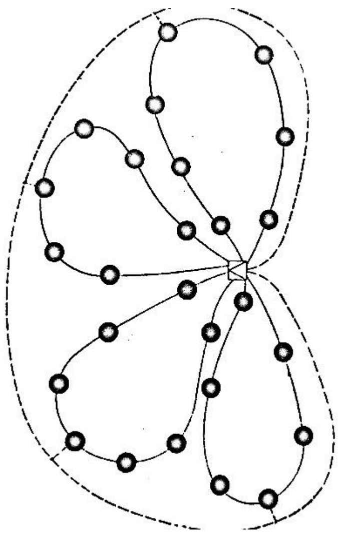


Figure 3-11 Petal scheme (Cataliotti 1983-1999)

3.1.3.5 Typical failure modes

When a failure in a power network occurs, is often difficult to identify which was the trigger because usually the grid is affected by cascading effects.

Nevertheless, it is possible to identify some typical failure modes of a network, referring to its main components:

- Substation: the first cause of failure is the collapse of the building where it is installed. In this thesis, this will be the most considered as the main failure mode and some photos and example will be presented.

  It is also possible that the substation fails cause of the overload of one of its main components, such as the transformers or other electrical equipment there installed.

- Utility pole: it is a post to support overhead power lines or other electrical equipment such as small transformers. It could be hit by overgrowing or falling trees. In the winter time, it is common that due to the ice some trees fall tearing down utility poles.

Figure 3-12 Falling tree on a power line due to the ice (Amoroso 2017)

Another failure cause could be the wind. Strong winds, especially during storms, caused big power outages in the history.

Usually, utility poles are not sensitive to earthquakes, due to their slenderness. Example of that was reported for wood posts in U.S. (Eidinger 2018).

- Overhead lines: the failure modes could be very similar to the ones of the utility poles. Moreover, the wind is the main problem, but sometimes it is correlated with other actions, such as the weight of the ice that in some cold areas stuck on the cables. These two are responsible for an increase in the mechanical stresses on the lines causing the failure of the network (Amoroso 2017).

Figure 3-13 Overhead power lines totally covered by ice (Amoroso 2017)

- Underground lines: the failure of these type of lines is mainly due to earthquakes. The imposed big ground deformations cause stresses and rupture in the cable installed underground.

  Another failure mode that is currently under investigation is the rupture of cable joints in the MV cables due to high temperatures (Pompili 2017).

Figure 3-14 Cable joint destroyed by high temperatures (Pompili 2017)

3.1.3.6 Focus on Transformers

Transformers are electromagnetic induction static devices, which modify voltages and currents from a primary circuit (receiver) to a secondary one (deliver) (Cataliotti 1983-1999).

Distribution transformers MV/LV have a three-column core, concentric windings, wire-wired conductors for small sections (i.e. high voltage and low current side), flat for the major (i.e. low voltage and high current side).

They can be classified according to some parameters:

- insulating material: used to be protected from high operating temperatures
- service and cooling mode
- nominal power: different kVA can be delivered
- installation method

Moreover, the installation type changes a lot country by country and there are some best practices common in the different continents.

These are the most used way to use transformers:

- Inside indoor MV/LV substations: Usually they are installed in the underground or first floor of residential buildings and all the feeders connected are cabled underground. These are the typical substations used in Italy.

Figure 3-15 Typical indoor MV substation (EEP Team 2018)

Usually, those system (Figure 3-16) are anchored at the substations wall.

Figure 3-16 Typical MV/LV distribution transformer (Direct Industry Team 2018)

- Installed in dedicated one/two-stories buildings: These are typically used in Italy in the countryside.

Figure 3-17 Italian two-stories substation

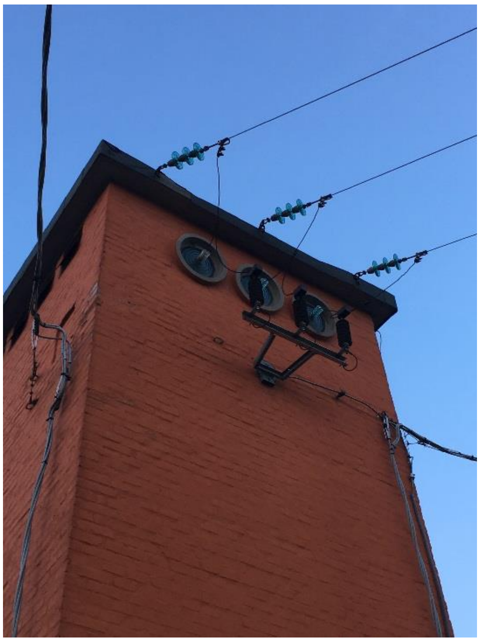


Figure 3-18 Details of an Italian two-stories substation

- Underground sited accessible from the street: these substations and the related equipment could be easily identified and inspected because are installed in public places.

Figure 3-19 Underground MV substation in Beirut, Lebanon. 2018

Figure 3-20 Detail of an underground MV substation in Beirut, Lebanon.

2018

- Pole-mounted transformers: in US and in Europe expecially in the countryside the equipment is installed outside hanged on posts.

Figure 3-21 Pole-mounted transform in Berkeley, California (USA). 2018

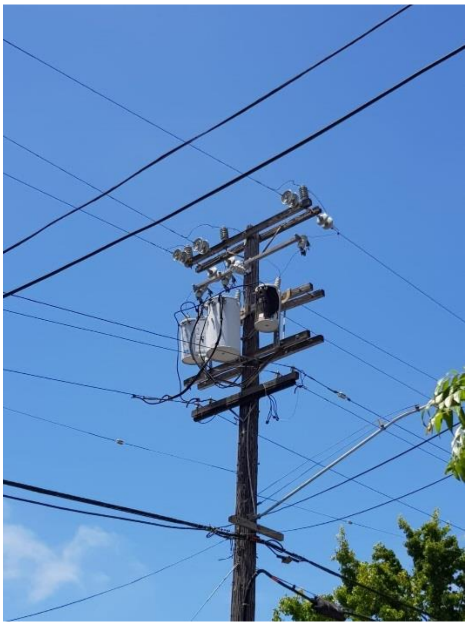


Figure 3-22 Detail of a pole-mounted transformer in Berkeley, California (USA). 2018

3.2 Literature review

In this review the relevant literature about resilience in urban power networks is presented. Many authors concerned with this problem using different application scales and methods. Starting from their pros and cons, a new methodology in the thesis is introduced.

The first step is to define the application scale, so the idea is to use a virtual city as testbed for resilience analyses. This is the approach used by the NIST-funded Centre for Risk-Based Community Resilience Planning (Unnikrishnan 2016).

They realized Centerville, a virtual community of approximately 50.000 people in a Midwestern State, and here different infrastructures are analysed, including the power network.

The EPN is characterized specifying the buses nodal coordinates (latitude and longitude) and a connectivity matrix is used to find the electrical path from the source node (generation plant) to the end node (typically the load point). The position of transmission towers and distribution poles is chosen, and the performance of the network are calculated with a specific index for storms STAIFI. The weaknesses of the Unnikrishnan's work are in the dimension of the city considered, because a town of only 50.000 people is not representative for a big city, and in the few numbers of electric buses taken in account. In addition to that, the design of the network should be modified, because the distances between towers and poles are constant and it is not realistic. In this thesis the reference map is a real city of one million of inhabitants and each district (called "circoscrizione") is independently modelled in detail.

The second step is to focus on the seismic hazard and to use the typical parameters of the earthquake engineering. This was made in an interesting work about Iran (Arghavani 2017). The International Institute of Earthquake and Seismology realized a prototype model for the transmission grid of the city of Qom. It is a centre with about one million inhabitants, for that reason the researchers built a simplified model of the network and some scenarios are shown. It is a connectivity analysis, i.e. a binary statement 0 or 1, where the vulnerability of tower and lines is modelled using weight factors. The recovery time and process are estimated and with a removal approach the grid resilience is evaluated with a set of different PGAs (Peak Ground Acceleration in [g]).

The weaknesses of this study are in dealing only with the transmission network when the focus is not a region but a city. Usually, in an urban environment the transmission buses are few and so, using a connectivity analysis with a so small number of elements, the losses are overestimated. In addition to that, this approach could be representative of the Iranian power networks, but not for the European or American ones, where the transmission towers are seismic isolated. They are not affected by earthquakes damages, except for big and rare events, and this position is confirmed by several publications (Eidinger 2018, Heunert 2018, Kotanidis 2018). Those authors state that the weak point of the electric power systems is in the level of substations and higher it is the voltage, higher it is the vulnerability (Heunert 2018). The damages are expected on high voltage equipment and in transformers. Some international codes and guidelines, such as the ESTI 248 or the IEEE 693, suggest different types of solutions to anchor properly the non-structural elements. These introductions lead to a real improvement in the networks behaviour, as reported by Eidinger after relevant events such as the South Napa and the Brea La Habra earthquakes (Eidinger 2018). In this thesis the transmission buses are considered undamaged in every scenario, and the losses are localized in the distribution ones where each substation is characterized by a distinct fragility model.

The third aspect is to identify a relevant and historical testbed to assess the performance of our new approach. This was the methodology used by Professor Shinozuka when he analysed the Los Angeles Department of Water and Power (Shinozuka 2004, Shinozuka 2007).

The database used is the 1994 Northridge earthquake effects on the distribution network and the hypothesis is to consider vulnerable only the transformers of the receiving stations.

Selecting a single scenario, the grid response and the power flow are analysed using a Monte Carlo approach associated to the fragility curves, i.e. curves that relates a certain PGA to a probability of an element failure. Observing these results, the authors computed risk curves and system performance criteria for the design.

The limit of this approach is to have all the parameters derived only from a single event. To make the analyses repeatable and more reliable the fragilities should be determined from independent evaluations and then verified with a testbed. This is the driven idea of thesis where the design and the fragility are firstly defined and at the end a relevant case study is performed.

A main aspect is to take in account not only the behaviour of the non-structural components, e.g. the transformers, but to model the buses from a structural point of view. This step forward is made in a study carried out in England (Panteli 2016).

Paper authors presents a comprehensive methodology for a multi-temporal & multi-regional resilience assessment of transmission systems to extreme weather conditions.

A structural model of the UK National Grid L2 transmission towers is analysed using the commercially available ABAQUS software. Beam finite elements are used to represent structural members. The forces on the structure are calculated using European codes and the UK national annexes.

Structural fragility curves for transmission elements are determined and Sequential Monte Carlo simulations are run to assess the impact of extreme weather on the grid.

The weak point of this paper is that is referred only to the transmission network, and the only hazard considered is the wind. An extension to other type of loads such as the seismic one should be implemented and changing the scale from the regional to the urban one could be an interesting step forward. In this thesis the transmission and distribution network are both considered, and the model is opened to future improvements including other types of hazard.

One of the principal references for this research is the work carried out by the Imperial College of London and Pontifical Catholic University of Chile

(Navarro-Espinosa 2017). A real distribution network in Chile is analysed under different scenarios.

The methodology proposed starts from the modelling of the earthquake and the substations fragility. Furthermore, the disaster impact is calculated through a sequential Monte Carlo simulation.

Thanks to a GIS approach to the problem, with the information about the epicentre and the intensity, an attenuation law is used to distribute the earthquake effects on a widespread area. This approach is then applied to some case studies and the grid resilience is evaluated in terms of Energy Not Supplied (ENS).

The limit of this study is to neglect the fragility of the buildings where the substations are located. In addition to that, only one curve for all the buses is considered. In the attenuation law geomechanical parameters should be taken in account and the results are expressed with only one index. In this thesis the substation fragility is related to the buildings fragility and the outputs are commented referring to the ENS and to other parameters just released from the Italian National Authority for Electricity Gas, Water and Wastes (The Italian National Authority for Electricity Gas Water and Wastes 2017). Distribution networks resilience is becoming part of the political and legislative discussion, so within March 2018, all Italian DSOs (Distribution System Operators) had to deliver a resiliency plan. The index suggested to compute their performances is the IRE (Index of REsilience) that takes in account the number of users disabled during a disaster and the return time of the event.

In this thesis the calculation of the ENS and the IRE is performed and the innovation in this approach is in introducing a new index that includes the vulnerability and the recovery time of a distribution network.

3.3 Resilience Indices

The Italian Regulatory Authority for Electricity Gas, Water and Wastes suggests to compute the resilience of an electric grid focus on the risk of disabling users in case of hazard or extreme weather conditions (The Italian National Authority for Electricity Gas Water and Wastes 2017).

This index is called IRI and is calculated as

$$IRI = NUD \cdot PD \tag{1}$$

where NUD is the number of LV users disabled and PD is probability of disservice. This chance is

$$PD = 1 / TR \tag{2}$$

where TR is the return time of the event, calculated in accordance with the European standard CEI EN 50341 (EN 50341-2-13). For a safe calculation we will take 50-years as return time.

An assessment of resilience can be obtained by computing the inverse of the risk index, thus obtaining

$$IRE = TR / NUD \tag{3}$$

where IRE is the resilience index or calculating the integer over time of the IRI index.

Another resilience rating can be given in term of ENS (Energy Not Supplied) to highlight the power delivered before the event and the time it takes to restore it.

This parameter is usually plotted in a graph where the kW/h lost are multiple with the hours or days of the progressive network restoration and the integer over time of this plot gives immediately a clear idea of an earthquake effects.

These two indices highlight some aspects of a power network failure, but they do not depict in complete way the concept of Resilience.

Resilience is a wide field that includes different areas such as the social science, economics, environmental consciousness and institutional studies.

This concept could be explained through four pillars, known as the four Rs (Cimellaro 2010, Cimellaro 2016) :

- Rapidity: it is the system capability to quickly react and achieve results to contain the human and economic losses
- Robustness: it is the "strength, or the ability of elements, systems or other units of analysis to withstand a given level of stress, or demand without suffering degradation or loss of function" (Bruneau and Wallace 2003)
- Redundancy: in this application, it is the possibility for a system to be fed through alternative paths, different from the classic ones, while this latter is under restoration
- Resourcefulness: it is the system managers capability to identify weaknesses and mobilize resources to reduce the effects of a likely damage

All these aspects are included in the new index here introduced, the Grid REsilience "GRE":

$$GRE = \int_{t_1}^{t_2} Trr \cdot n_{sub\_undam} \cdot AltPath \cdot Gen \cdot dt \qquad (4)$$

Where,

$Trr =$ Transformers Restoration Rapidity, and this is equal to 1 when only the 0.4 MVA is present, 0.67 when classes 0.4 and 0.63 MVA are present and 0.57 when classes 0.4, 0.63 and 1 MVA are present. This concept and these values are derived from FEMA data about transformers restoration.

$n_{sub\_undam} =$ it is percentage of undamaged substations. It is expressed as the ratio between the number of undamaged substations after a scenario and the total number of substations. This clearly represents the network robustness.

$AltPath =$ it is related to the existence in a neighbourhood of alternative paths to be fed by bordering areas. This value change in a range between 0 and 1 due to non-existence ("0" case) of alternative paths up to 1 that means that the 100% of neighbourhoods are each other linked.

$Gen =$ it is related to the availability of portable generators to use in the first hours after a disaster. This value change in a range between 0 and 1 due to the lack of generators in the region ("0" case) up to 1 that means that the all the recovery areas could be quickly fed with electricity with these temporary solutions. This is power network resilience from the users' point of view and it is managed not by the city electric company but usually by the Civil Protection Department.

t_1 and t_2 are the observation time range boundaries of the emergency.

For sake of clarity, the GRE is not a resilience evaluation at a specific time, but it must be considered the overall evolution over time of the parameters herein included. This is the reason why the integral operator is used.

This equation is the electric version of the resilience definition given by Cimellaro et al. (Cimellaro 2010). As matter of fact, this is the integral over time of network functionality during its life cycle decomposed in some relevant parameters. As will be presented in the following examples, the coefficient related to the rapidity and the recovery-time changes the slope of the function and robustness is calculated as the complementary of the losses. The losses here considered are the direct economic ones, so they represent the "mainly physical structural and non-structural losses" (Cimellaro 2010) and in this case study, they are computed with the direct evaluation of the substations failed. The recovery function used is the linear one because a conservative approach was followed, as the preparedness and the societal response are still under study.

The step forward of the GRE index is to finally identify coefficient to quantify the redundancy and resourcefulness in the electric field.

3.4 Case study: Ideal City

After introducing the indices to measure a distribution grid resilience, the intention is to test these parameters on a real testbed.

In the Ideal City project, the electric power network was not already designed by previous colleagues, so several ways were considered to realize the grid.

Real data was not available because the electric companies do not want to share sensitive data for external researches, so the only solution was to design entirely the network.

This is not the classical procedure in electrical engineering where the buses information about position, power, and voltages are known and the effort is in improve or add new elements to an existing grid. In addition to that, this comprehensive approach to city resilience is not common in this field, because only recently the Italian government asked for a resilience plan and so a general overview of the network weaknesses was required.

For the designing, different electrical software were evaluated, such as DigSILENT PowerFactory, PSS@SINCAL, and EasyPower, but they are more useful when the grid is small and so it is realistic to detail each line and substation. If the focus were a city block or a district with more parameters known, one of those software could be the right solution. Dealing with a city-scale problem with few information available, two approaches were followed, due to different purposes.

The first approach is to refer to a package of standard networks developed by the European Commission in collaboration with the Joint Research Centre and all the Distribution System Operators active in Europe. These data are a solid basis to start facing the problem and to try different solutions. Obviously, being a testbed developed for general purposes, it is not a flexible tool easy applicable to every situation.

The second approach was to design an independent grid specifically for Ideal City following some rules usually taken in account in the electrical engineering. The performances and the results with this approach are better, but the workload and the difficulties faced were several.

In all these tempts, the work was supervised by Professor A. Mazza of the Electrical Department of the Politecnico di Torino.

3.4.1 Similarities Design Method

3.4.1.1 Method description

As stated, the main problem faced in this type of research is the limited data availability and the first approach followed was to use an existing testbed. Therefore, the idea is to try to find an electric grid compatible with the map of Ideal City. The approach selected is summarized in Figure 3-23.

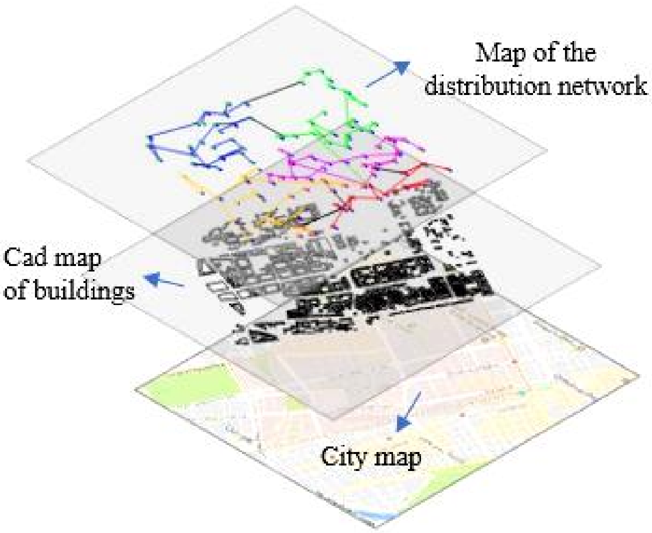


Figure 3-23 Summary of the approach

The European Commission in collaboration with the Distribution System Operators Observatory of JRC (Joint Research Centre) released a technical report (Prettico 2016) about representative networks. They have collected data from 79 out of 190 European DSOs, that are representative of the 70% of the electricity supplied by all DSOs serving over 100,000 customers. They distribute more than 2,000 TWh of electricity to over 200 million customers per year, covering a total area of more than 3 million square km.

This information has been used to build 36 indicators about network structure, network design and distributed generation. From 10 of these indicators representative distribution networks have been obtained using RNM (Reference Network Model). This is a useful software for large scale distribution planning developed by the Universidad Pontificia Comillas (Domingo 2011).

In particular “urban” network from JRC database is used for the most densely populated districts and the “semi-urban” one for the surrounding areas.

The second step is to make this network independent from the map that JRC has used to realize the model. In these files, information about HV (high voltage), MV (medium voltage) and LV (low voltage) buses with coordinates, branches, electric parameters and protections are provided. To apply this realistic network to Ideal City, LV data are relevant only for defining the total amount of consumers, not for their real positions. So, only HV and MV buses are explicitly considered in the model. Finally, the network model is rebuilt writing a new description.

The network has not been freely designed, but it has been strictly controlled using Matpower6.0, a package of MATLAB M-files (Natick: The MathWorks Inc. 2018) for solving power flow and optimal power flow problems developed by PSERC (Power Systems Engineering Research Centre) at Cornell University (Zimmerman 2011).

The method for the network performance analysis consists in the computation of the load flow on the entire damaged grid. In this way, a higher precision respect to a simpler and faster connectivity analysis (Arghavani 2017) is provided.

Analyses made by Matpower follow the Newton Raphson (NR) algorithm, which solves this nonlinear equation problem.

In the AC power flow problem (Zimmerman 2011), the nodal bus injections are matched to the injections from loads and generators. The power balance equations are expressed in complex matrix form as

$$g_S(V,Sg) = S_{bus}(V) + S_d - C_g S_g = 0 \tag{5}$$

where $S_{bus}(V)$ is the complex power injections as functions of the complex bus voltages V, S_d are constant power loads, S_g is the generator injections and the C_g is the connection matrix.

This problem can be split into its real P and reactive Q components:

$$g_P(\theta, V_m, P_g) = P_{bus}(\theta, V_m) + P_d - C_g P_g = 0 \tag{6}$$

$$g_Q(\theta, V_m, Q_g) = Q_{bus}(\theta, V_m) + Q_d - C_g P_g = 0 \tag{7}$$

where θ is the voltage angle and V_m is the voltage magnitude. The power flow problem could be a set of equations in the form

$$g(x) = 0 \tag{8}$$

And in particular

$$g(x) = \begin{bmatrix} g_P(\theta, V_m, P_g)\, for\ PV\ and\ PQ\ buses \\ g_Q(\theta, V_m, Q_g)\, for\ PQ\ buses \end{bmatrix} \tag{9}$$

where PQ buses are pure load buses and they represent the major part of all of network buses. In these elements P and Q are defined, but θ and V_m must be calculated.

PV buses are connected to the generator and they are a small part of all buses. In these elements P and V_m are defined, but Q must be calculated (Grainger 1994).

It is also important to specify the value of x, as:

$$x = \begin{bmatrix} \theta \text{ for all buses except Reference bus} \\ V_m \text{ for PQ buses} \end{bmatrix} \quad (10)$$

where the Reference bus is the slack bus and it is considered as the number one of the networks. In this element, $\theta = 0^o$, V_m is known but P and Q must be computed.

So, a nonlinear system (Dharamjit & Tanti 2012) with $n_{pv} + n_{pq}$ equations and unknowns (n is the number of PV or PQ buses) results. Solving by x, it's possible to determine the generator real power injections at the reference bus and generator power injections.

These solutions are provided using the iterative NR's method. Starting from an initial trial solution, at each iteration, a tolerance must be smaller than a predetermined threshold. So, the passages are these:

It starts with

$$\left[g(x)\right] = \begin{bmatrix} \tilde{g} \end{bmatrix} \quad (11)$$

the solution at first iteration is

$$\left[x\right] = \left[x^{(0)}\right] = \left[x^{(k)}\right] \quad (12)$$

and the following ones in general are expressed as

The tolerance is computed as

$$\left[\varepsilon^{(k)}\right]=\left[\tilde{g}\right]-\left[g(\left[x^{(k)}\right])\right] \tag{13}$$

If the tolerance doesn't become smaller than the threshold, the function $[g(x)]$ is represented as a series, involving the Jacobian matrix computed at $[x]=[x^{(k)}]$. They can be written as $[J^{(k)}]$.

Finally

$$\left[g(\left[x^{(k)}\right])\right]+\left[J^{(k)}\right]\cdot\left[\Delta x^{(k)}\right]=\left[\tilde{g}\right] \tag{14}$$

and so

$$\left[J^{(k)}\right]\cdot\left[\Delta x^{(k)}\right]=\left[\varepsilon^{(k)}\right] \tag{15}$$

The NR's method linearizes the nonlinear system and, therefore, the Jacobian matrix is composed by constant values function of the unknows.

After the modelling of the network, the load flow is computed through the MATLAB code (Natick: The MathWorks Inc. 2018). If the NR's method converges (Figure 3-24) in few iterations and the power restraints are respected, the grid is properly designed.

```
Newton's method power flow converged in 5 iterations.

Converged in 0.78 seconds
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses            166     Total Gen Capacity    1000.0        -1000.0 to 1000.0
Generators         1     On-line Capacity      1000.0        -1000.0 to 1000.0
Committed Gens     1     Generation (actual)     89.5              37.9
Loads            164     Load                    88.5              26.5
  Fixed          164       Fixed                 88.5              26.5
  Dispatchable     0       Dispatchable          -0.0 of -0.0      -0.0
Shunts             0     Shunt (inj)             -0.0               0.0
Branches         170     Losses (I^2 * Z)         1.00             11.35
Transformers       1     Branch Charging (inj)     -                0.0
Inter-ties         0     Total Inter-tie Flow     0.0               0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.984 p.u. @ bus 3192      1.002 p.u. @ bus 3160
Voltage Angle      -6.52 deg   @ bus 3192      0.00 deg   @ bus 1
P Losses (I^2*R)             -                 0.32 MW    @ line 1-3160
Q Losses (I^2*X)             -                10.81 MVAr  @ line 1-3160
```

Figure 3-24 Example of convergence with the NR's method and restraints for a hypothetic network

3.4.1.2 Network description

The case study employed for the application of the method consists in the Ideal City's district of Crocetta. It is a very central and urbanized area of Turin, full of residential buildings, offices and schools such as the university Politecnico di Torino. The population is about 40,000 people. During the day, such number of population increases.

So, the “urban" network from the JRC database is employed and adapted to the Crocetta's case, being suitable for about 50,000 users. Figure 3-25 shows the satellite image of the considered district.

Figure 3-25 Crocetta’s picture from the satellite with its borders highlighted in red

The grid is composed by five feeders, which supply 12735 housing units (supposing a mean of 4 people per unit) and 38 MV consumers. There is only one HV/MV substation from 132 to 20 kV with 80 MVA of rated power and 126 MV/LV substations from 20 to 0.4 kV (Prettico 2016). About the latter 126 MV/LV substations, they are detailed in Table 2.

Table 2 Number of transformers per each class

Rated Power (kVA)	Number
1000	34
630	52
400	40

This distribution network is presented in Figure 3-26, while Figure 3-27 shows the overlap of the same grid with the district map, as obtained by some simplification from the real map of Turin (Zamani Noori 2017).

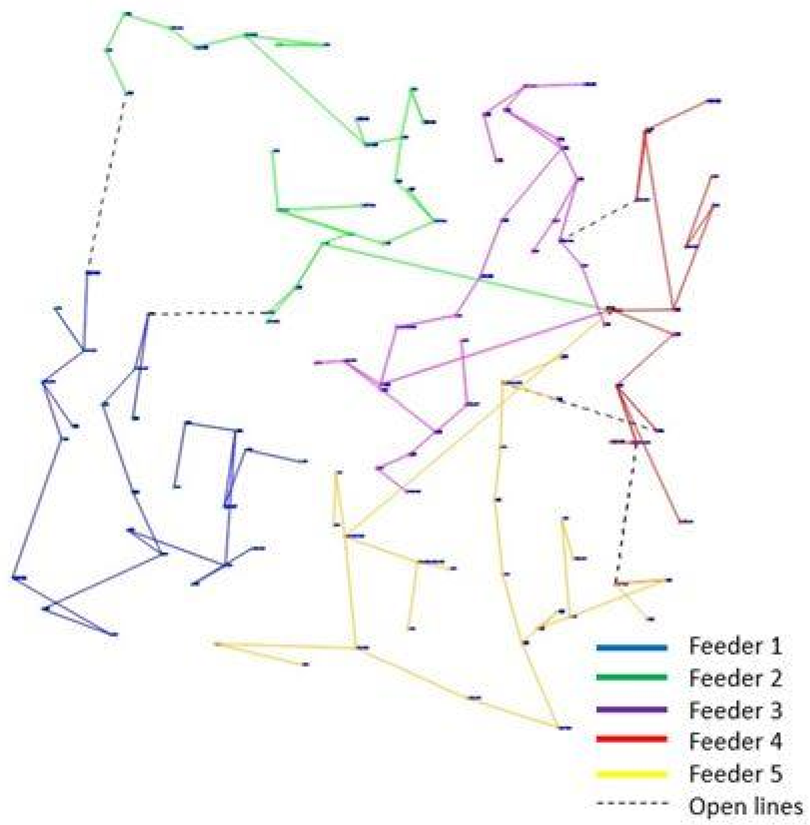


Figure 3-26 Urban network with MV buses in evidence

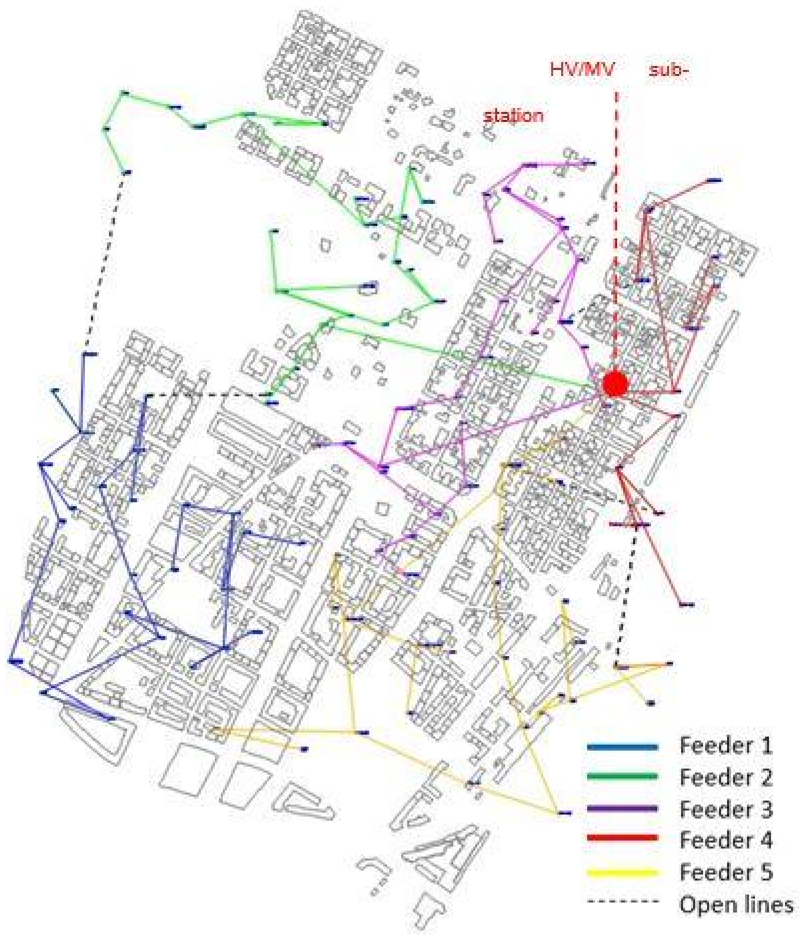


Figure 3-27 Overlap buildings-network

3.4.2 Density Design Method

3.4.2.1 Method description

Due to the many disadvantages found in the use of the previous method a new approach was performed. Indeed, it could be hard to find every time district typology that allows an easy overlap with a standardized grid.

Instead of referring to a database, the purpose is to design the grid. In this new methodology there are three main design parameters:

- The population and the related density
- The load density
- Electrical engineering constraints (e.g. feeders' length, load types, buses redundancy, etc.)

After some tests this method was applied to the entire city of Turin designing the distribution power network district by district referring to the "Circoscrizioni" in which the city is divided (Comune di Torino 2018).

Table 3 Circoscrizioni composition (Comune di Torino 2018)

Circoscrizione	**Neighbourhood**
1	Centro, Crocetta
2	Santa Rita, Mirafiori Nord
3	Borgo San Paolo, Cenisia, Pozzo Strada, Cit Turin, Borgata Lesna
4	San Donato, Campidoglio, Parella
5	Borgo Vittoria, Madonna di Campagna, Lucento, Vallette
6	Barriera di Milano, Regio Parco, Barca, Bertolla, Falchera, Rebaudengo, Villaretto,
7	Aurora, Vanchiglia, Sassi, Madonna del Pilone, San Salvario, Cavoretto, Borgo Po

8	San Salvario, Cavoretto, Borgo Po
9	Nizza Millefonti, Lingotto, Filadelfia
10	Mirafiori Sud

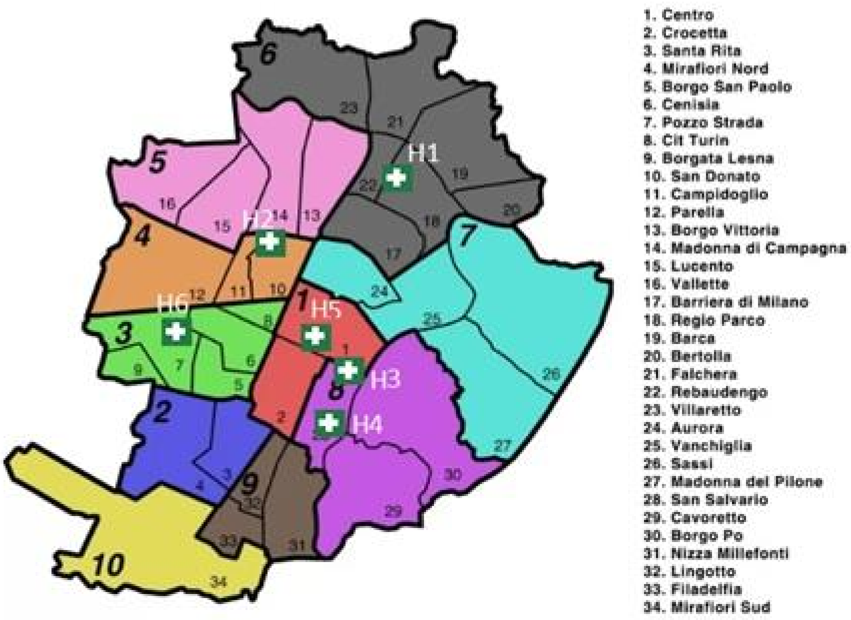


Figure 3-28 Map of Turin neighbourhoods (Comune di Torino 2018)

District by district different MV schemes were applied and the substations specifications will be provided. The software used are AutoCAD (Autodesk 2014) and QGIS (QGIS Development Team 2016).

All the MV substations have a voltage 22 kV and the loads are chosen according to the European technical report (Prettico 2016). In Table 4 there is the distribution of loads assumed referring to the best practice.

Table 4 Types of load

Type of Transformer [kVA]	Percentage
400	60%
630	30%
1000	10%

In the computation of number of users, for each esteemed LV bus it is assumed the presence of four people.

All the data related to the City of Turin are taken from city official reports (Comune di Torino 2018).

3.4.2.2 Network description

On the basis of the design parameters just presented, below are listed the input characteristics for the design and output of the network, district by district. At the end the entire city network will be presented with a comparison with the real data provided by IRETI, the Turin electricity distribution authority.

Circoscrizione 1

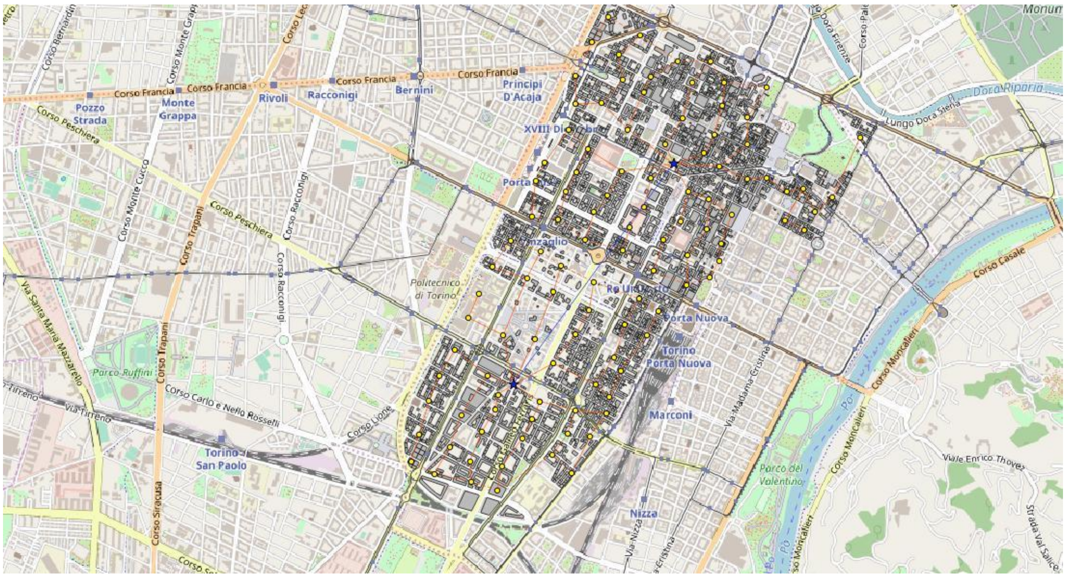


Figure 3-29 Circoscrizione 1 power grid

Table 5 Circoscrizione 1 Design Input Data

Parameters	**Values**
Area	6.879 km^2
Population Density	11,651.06 ab/km^2
Population	80,152
Designed Load density	8 MVA/km^2
MVA estimated	55
Number of buses estimated	104

Table 6 Circoscrizione 1 Design Output Data

Parameters	**Values**
0.400 MVA buses installed	65
0.630 MVA buses installed	33
1 MVA buses installed	10
Number of buses installed	108
Number of users supplied	81,034

Circoscrizione 2

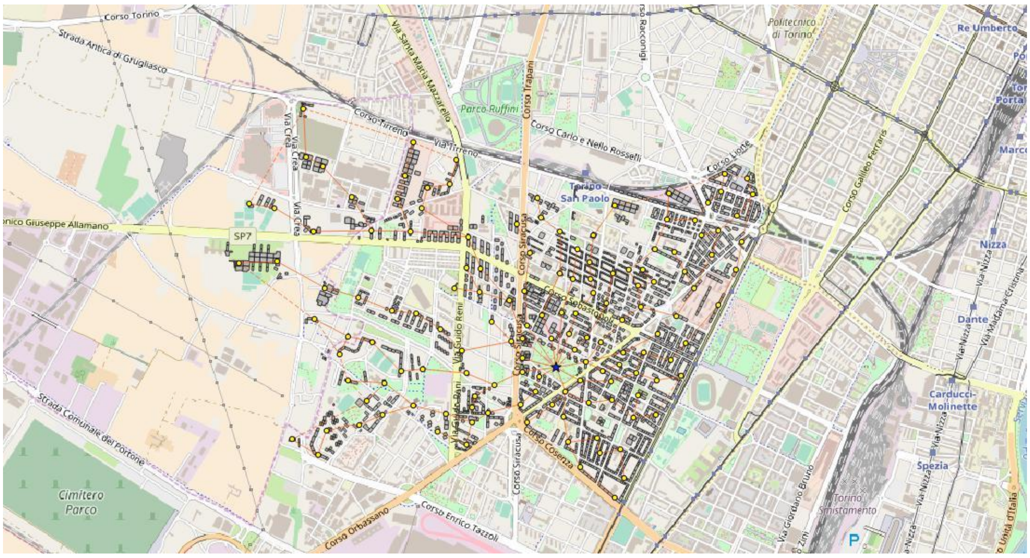


Figure 3-30 Circoscrizione 2 power grid

Table 7 Circoscrizione 2 Design Input Data

Parameters	Values
Area	7.313 km^2
Population Density	14,523.78 ab/km^2
Population	106,209
Designed Load density	10 MVA/km^2
MVA estimated	73
Number of buses estimated	138

Table 8 Circoscrizione 2 Design Output Data

Parameters	Values
0.400 MVA buses installed	85
0.630 MVA buses installed	43
1 MVA buses installed	14
Number of buses installed	142
Number of users supplied	107,190

Circoscrizione 3

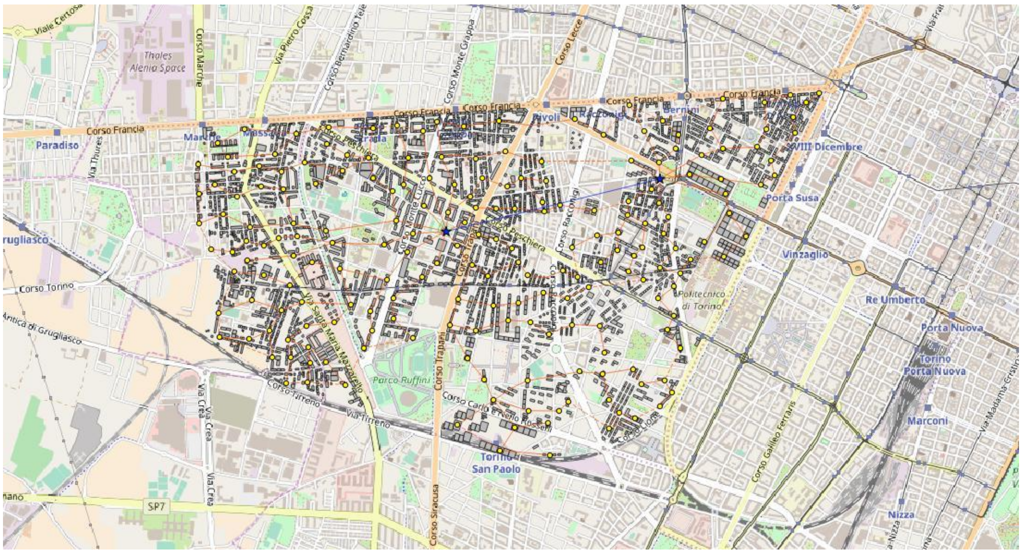


Figure 3-31 Circoscrizione 3 power grid

Table 9 Circoscrizione 3 Design Input Data

Parameters	**Values**
Area	8.604 km^2
Population Density	14,936.42 ab/km^2
Population	128,512
Designed Load density	10 MVA/km^2
MVA estimated	86
Number of buses estimated	163

Table 10 Circoscrizione 3 Design Output Data

Parameters	**Values**
0.400 MVA buses installed	124
0.630 MVA buses installed	62
1 MVA buses installed	21
Number of buses installed	206
Number of users supplied	155,000

Circoscrizione 4

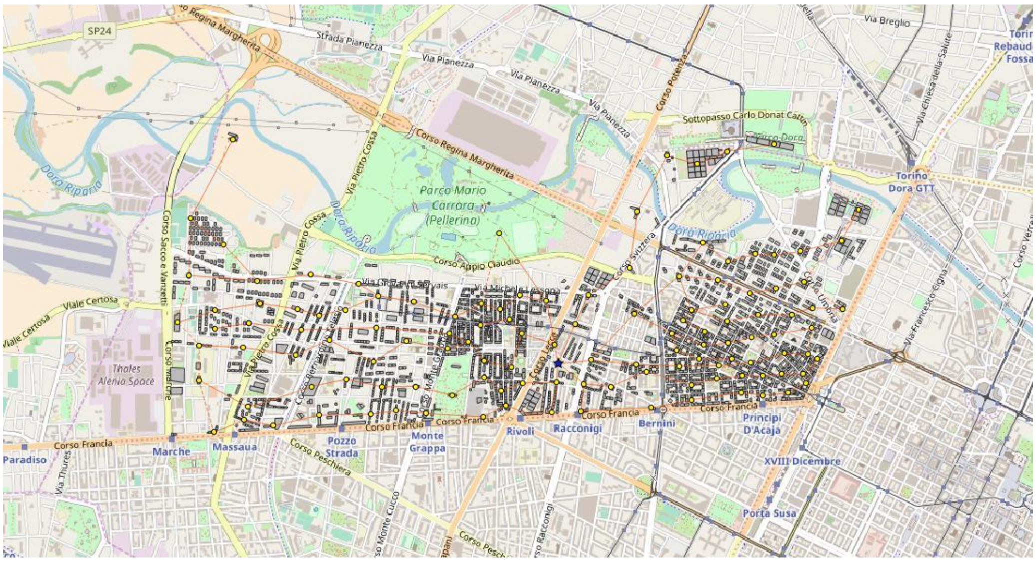


Figure 3-32 Circoscrizione 4 power grid

Table 11 Circoscrizione 4 Design Input Data

Parameters	**Values**
Area	9.093 km^2
Population Density	10,367.80 ab/km^2
Population	94,271
Designed Load density	7 MVA/km^2
MVA estimated	64
Number of buses estimated	121

Table 12 Circoscrizione 4 Design Output Data

Parameters	**Values**
0.400 MVA buses installed	75
0.630 MVA buses installed	38
1 MVA buses installed	12
Number of buses installed	125
Number of users supplied	94,357

Circoscrizione 5

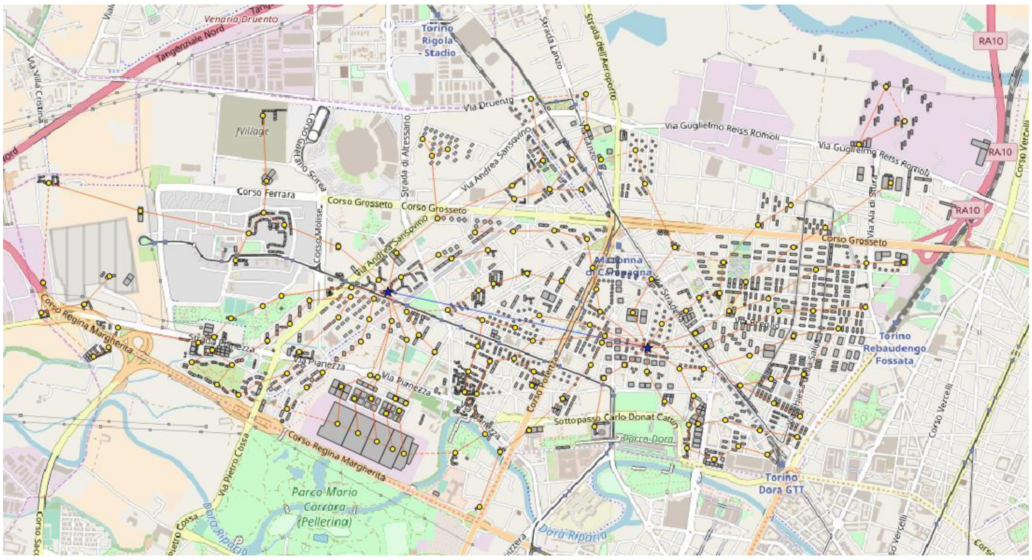


Figure 3-33 Circoscrizione 5 power grid

Table 13 Circoscrizione 5 Design Input Data

Parameters	Values
Area	15.461 km^2
Population Density	7,823.99 ab/km^2
Population	120,967
Designed Load density	4.5 MVA/km^2
MVA estimated	70
Number of buses estimated	132

Table 14 Circoscrizione 5 Design Output Data

Parameters	Values
0.400 MVA buses installed	100
0.630 MVA buses installed	50
1 MVA buses installed	17
Number of buses installed	167
Number of users supplied	126,061

Circoscrizione 6

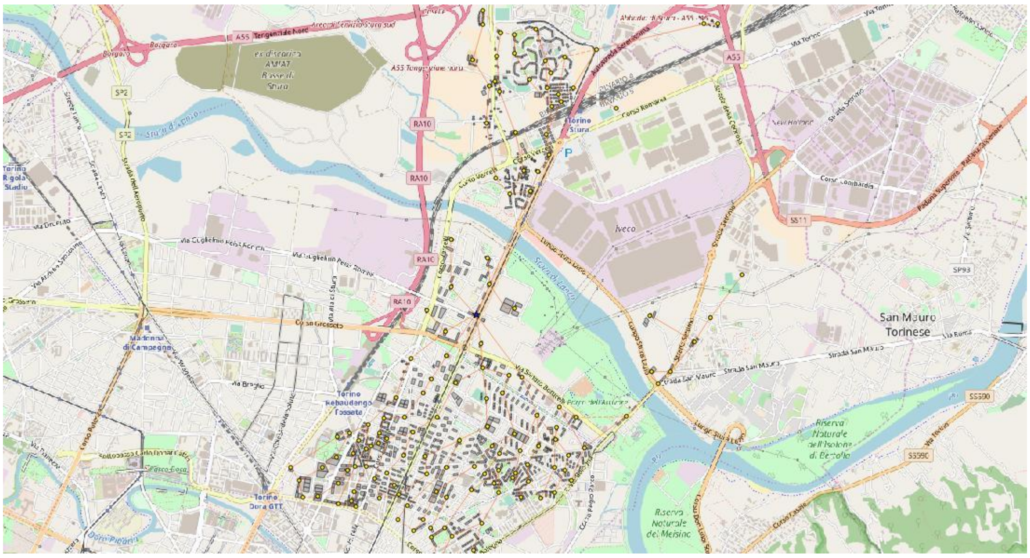


Figure 3-34 Circoscrizione 6 power grid

Table 15 Circoscrizione 6 Design Input Data

Parameters	**Values**
Area	25.460 km^2
Population Density	4,050.47 ab/km^2
Population	103,125
Designed Load density	3 MVA/km^2
MVA estimated	76
Number of buses estimated	144

Table 16 Circoscrizione 6 Design Output Data

Parameters	**Values**
0.400 MVA buses installed	84
0.630 MVA buses installed	42
1 MVA buses installed	14
Number of buses installed	140
Number of users supplied	105,680

Circoscrizione 7

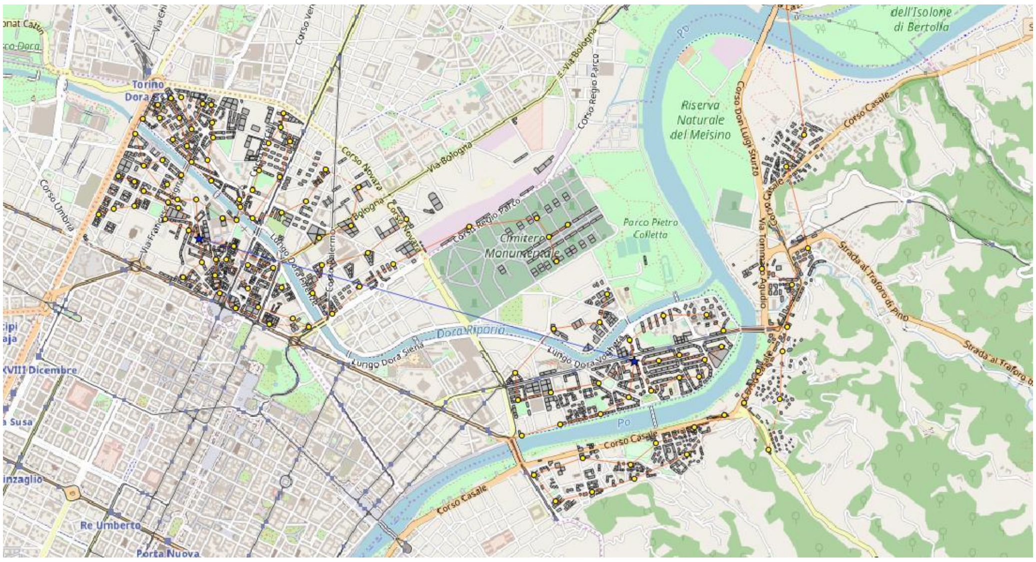


Figure 3-35 Circoscrizione 7 power grid

Table 17 Circoscrizione 7 Design Input Data

Parameters	Values
Area	22.330 km^2
Population Density	3,913.88 ab/km^2
Population	87,398
Designed Load density	MVA/km^2
MVA estimated	67
Number of buses estimated	127

Table 18 Circoscrizione 7 Design Output Data

Parameters	Values
0.400 MVA buses installed	75
0.630 MVA buses installed	38
1 MVA buses installed	12
Number of buses installed	125
Number of users supplied	94,357

Circoscrizione 8

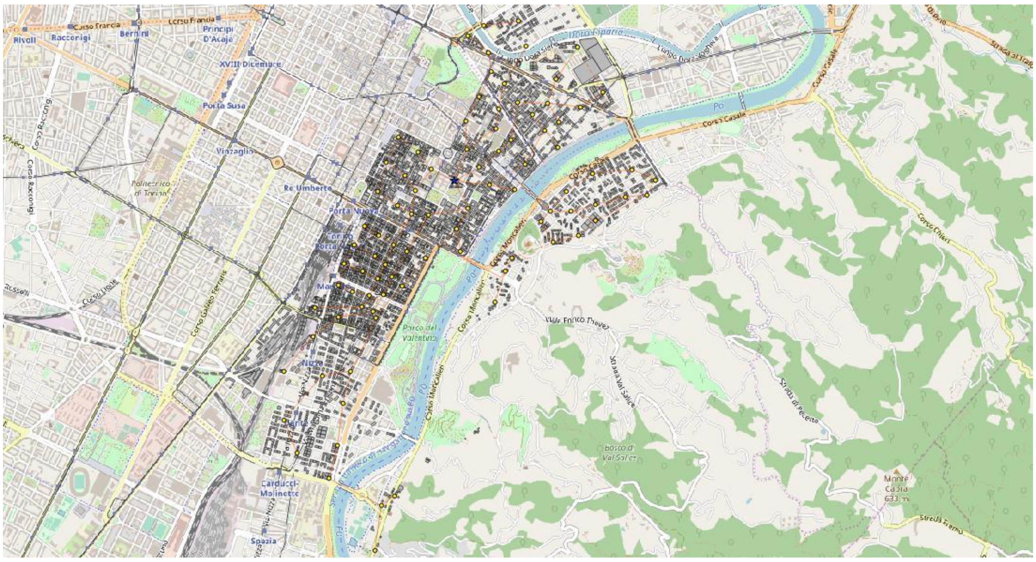


Figure 3-36 Circoscrizione 8 power grid

Table 19 Circoscrizione 8 Design Input Data

Parameters	Values
Area	16.602 km^2
Population Density	3,498.55 ab/km^2
Population	58,084
Designed Load density	3 MVA/km^2
MVA estimated	50
Number of buses estimated	95

Table 20 Circoscrizione 8 Design Output Data

Parameters	Values
0.400 MVA buses installed	55
0.630 MVA buses installed	27
1 MVA buses installed	9
Number of buses installed	91
Number of users supplied	68,692

Circoscrizione 9

Figure 3-37 Circoscrizione 9 power grid

Table 21 Circoscrizione 9 Design Input Data

Parameters	Values
Area	6.518 km^2
Population Density	11,757.02 ab/km^2
Population	76,627
Designed Load density	8 MVA/km^2
MVA estimated	52
Number of buses estimated	98

Table 22 Circoscrizione 9 Design Output Data

Parameters	Values
0.400 MVA buses installed	63
0.630 MVA buses installed	32
1 MVA buses installed	10
Number of buses installed	105
Number of users supplied	79,260

Circoscrizione 10

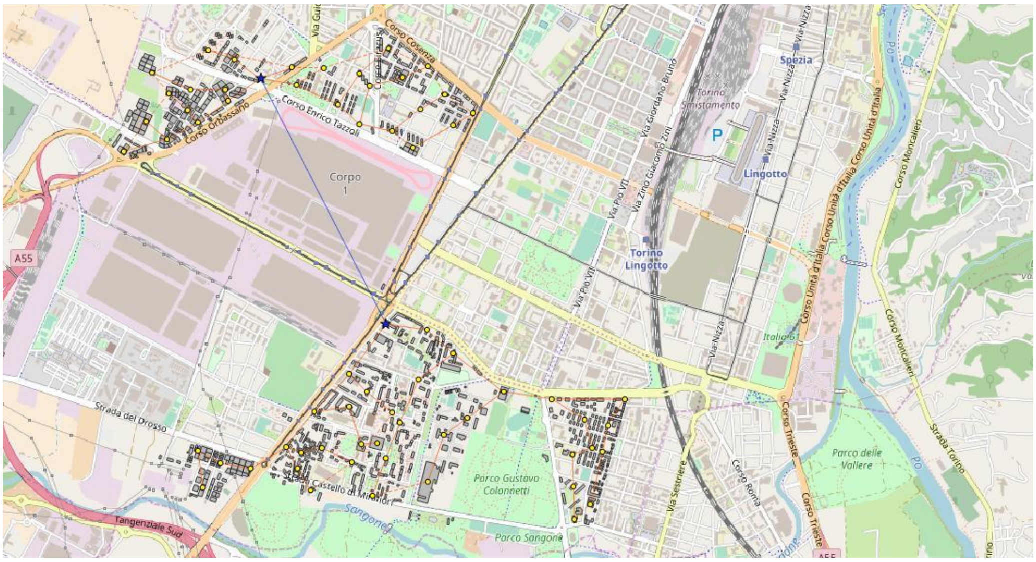


Figure 3-38 Circoscrizione 10 power grid

Table 23 Circoscrizione 10 Design Input Data

Parameters	Values
Area	11.739 km^2
Population Density	3,394.69 ab/km^2
Population	39,851
Designed Load density	3 MVA/km^2
MVA estimated	36
Number of buses estimated	68

Table 24 Circoscrizione 10 Design Output Data

Parameters	Values
0.400 MVA buses installed	39
0.630 MVA buses installed	20
1 MVA buses installed	6
Number of buses installed	65
Number of users supplied	49,066

City of Turin

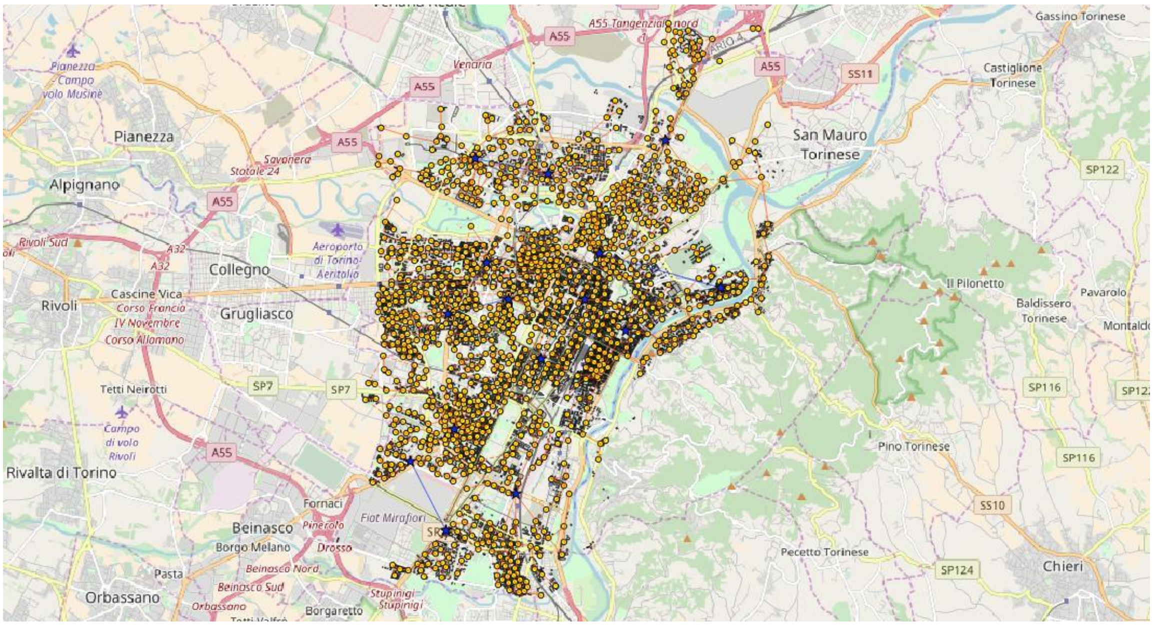


Figure 3-39 Turin power grid

In figure 3-39 there is the final map of the distribution power network designed for the city of Turin.

In each district it was considered to have only one HV/MV substations and where it is needed cause of a big extension a second central bus is installed as MV/MV.

At the end it is possible to make a comparison between the designed network and some real data from the Turin electricity utility, IRETI (IRETI 2016). At this regard, please notice that the MV/LV data given by the company is referring to all the type of costumers, both residential and industrial ones. In U.S. the 37% of the electricity consumption is for residential purpose (Salman 2016), so that value is used as reference.

Table 25 IRETI Data (IRETI 2016)

Parameters	Values
HV/MV buses	9
MV/LV buses	2,945
MV/LV residential buses (esteemed)	1,090

Table 26 Comparison IRETI data – Density Designed Network

Parameters	Values
HV/MV buses	10
MV/LV residential buses	1,274

Evidentially, data from IRETI and data from the method here proposed are very similar and this is good validation for the analysis assessed. Some uncertainties are still present because the real position of MV/LV buses is not known.

3.4.3 First approach: Similarities Designed Network, Fragility & Resilience

With the Similarities Design Method the case study is limited only to the Crocetta neighbourhood and to analyse the effects of a possible earthquake first the network fragility must be defined. So, the assumption is to concentrate the fragility in the medium voltage substations.

To model their fragility researchers have used the HAZUS®-MH MR5 (FEMA 2002) that provides sets of fragility curves for unanchored elements. This means that the components are assumed without any seismic protection and designed with normal requirements. This hypothesis is introduced because the goal is to estimate the worst-case scenario's probability of exceedance.

Medium voltage substations are composed by important equipment as transformers, switches, circuit breakers etc. Furthermore, they are assumed as installed in buildings, so they can be also affected by the structural damages. Table 27 reports the damage conditions.

Table 27 Description of damage states

Damage state	**Description**
Complete	component OR building 100% damage
Extensive	component OR building 70% damage
Moderate	component OR building 40% damage
Minor	component OR building 5% damage

Fragility curves of the components implement the PGA as seismic intensity parameters. They are lognormal function defined through logarithmic mean λ and logarithmic standard deviation ß. Table 28 summarizes the implemented fragility curves parameters. Figure 3-40 depicts the resulting fragility functions.

Table 28 Fragility parameters for medium voltage substations with unanchored components (Cavalieri 2014)

Damage state	**λ**	**ß**
Complete	-0.69	0.4
Extensive	-1.2	0.4

Moderate	-1.61	0.5
Minor	-2.3	0.6

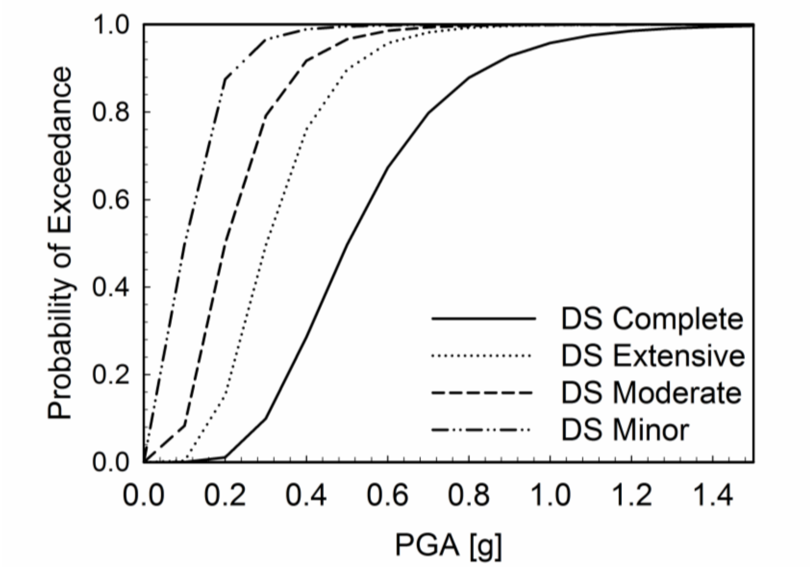


Figure 3-40 Fragility curves for medium voltage substations with standard components

The simulation considers an increasing set of PGAs and the resulting outcomes of the network are evaluated. In these scenarios, MV substations failed and consumers are without power.

The resilience of the system is evaluated in terms of MW lost due to people without electricity for a certain period, costs and time due to repair activities. About the restoration consequences, authors refer to HAZUS Technical Manual (FEMA 2002). Figure 3-41 reports the adopted restoration functions.

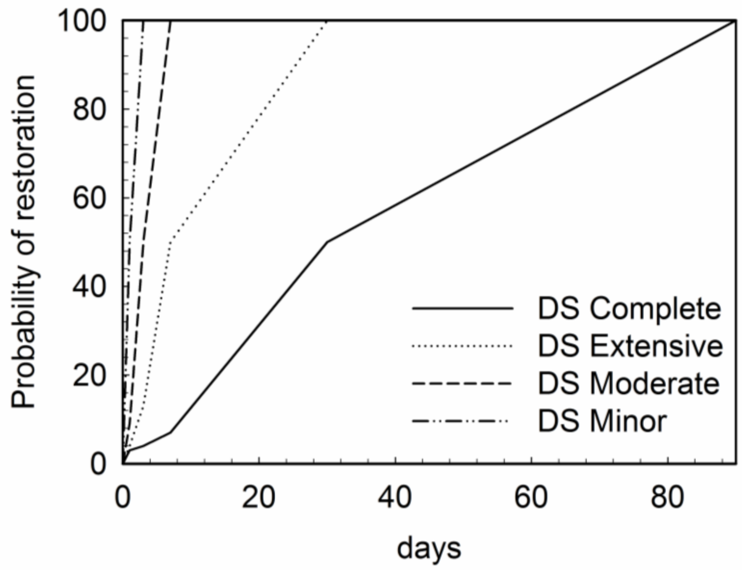


Figure 3-41 Discretized Restoration Functions for electric substations

In the restoration analyses the focus is moved on transformers because they can be considered the most critical substations components.

In Table 29 there are the five classes of transformers (Prettico 2016) used.

Table 29 Classes of transformers and related networks

Transformers power (kVA)	Network
100	Semi-urban
250	Semi-urban, Urban
400	Semi-urban, Urban
630	Urban
1000	Urban

About transformers costs, authors refer to PACT, a FEMA tool to analyse the seismic performance assessment of structural and non-structural components (FEMA 2016). Data are given in US dollar (USD) but they have been converted in euros (€) with 1.2 as exchange rate (Figure 3-42).

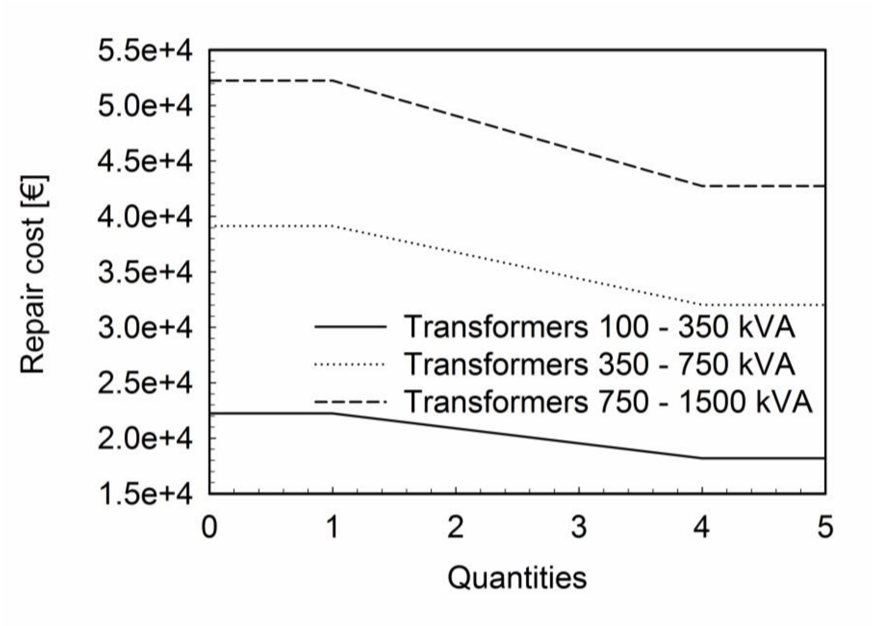


Figure 3-42 Repair cost of transformers related to their quantities

It is also important to take in account the correlation between the damage state and the transformers serviceability and power availability, as Table 30 summarizes.

Table 30 Relation damage state – power supply

Damage state	Serviceability	Power
Complete	Not Repairable	No
Extensive	Operational after repairs	No
Moderate	Operational without repairs	Reduced
Minor	Operational without repairs	Reduced

In this work, repair costs and down time analysis are evaluated, so it is supposed to refer to a “damage state” situation for the network. In particular, “extensive” damage in Table 27 (with no power and “Operational after repairs” conditions) for the network is considered. It is assumed that power can be feed only after grid restoration, which consists in components repairing. So, no portable generators are used. Indeed, resilience is studied for limited damage conditions, not for complete damage of components and buildings.

The correspondent fragility curve (Figure 3-40) shows that up to 0.2g the grid does not suffer any damage. From 0.3g level, substations have the 50% probability of exceedance and with a 0.5g this percentage goes to about 90%.

So, an event with a magnitude between 0.3g-0.5g, can cause the power interruption and the steps until the complete restoration are considered for the present application.

Observing the repair time for MV buses, that is the substation (Figure 3-41), there is more than 50% chance of having the complete restoration in less than 10 days. In the following, the transformers case is analysed in detail and the repairs specifications (FEMA 2016) are shown is in steps (Table 31).

Table 31 Steps of repairs

After	Transformers repaired
4 days	400 kVA
6 days	400, 630 kVA
7 days	400, 630, 1000 kVA

To give an assessment of resilience we calculate the IRI risk index. Note that all graphs start with a plateau to evaluate the initial condition of 100% functionality and then the event is considered to occur between hypothetical days 1 and 2 of the simulation (Figure 3-43). After these 24 hours, the action of the disservice causes is considered exhausted and the assessment of the consequences can be started. In these plots, a polyline is used due to the event discretization.

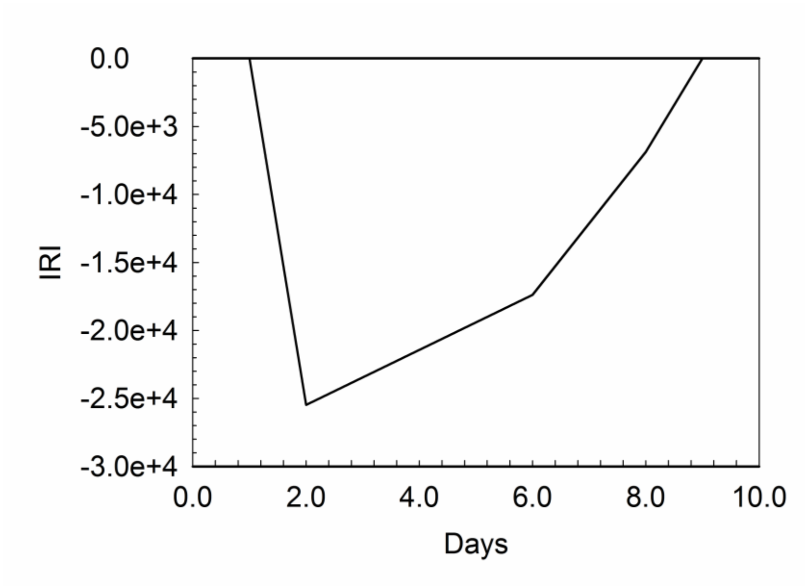


Figure 3-43 IRI index

The focus is on the users disabled and, in this example, more than 12,000 users are without electricity. The area under the IRI vs Days curve is the IRE evaluation and this plot highlights the big improvements needed by the grid in terms of more robustness of the buses and more rapidity in the restoration process. After 4 days, the electricity is resupplied only to the 25% of the population.

A second evaluation can be given in terms of lost energy, the ENS trend is as follows using a unitary power factor (Figure 3-44).

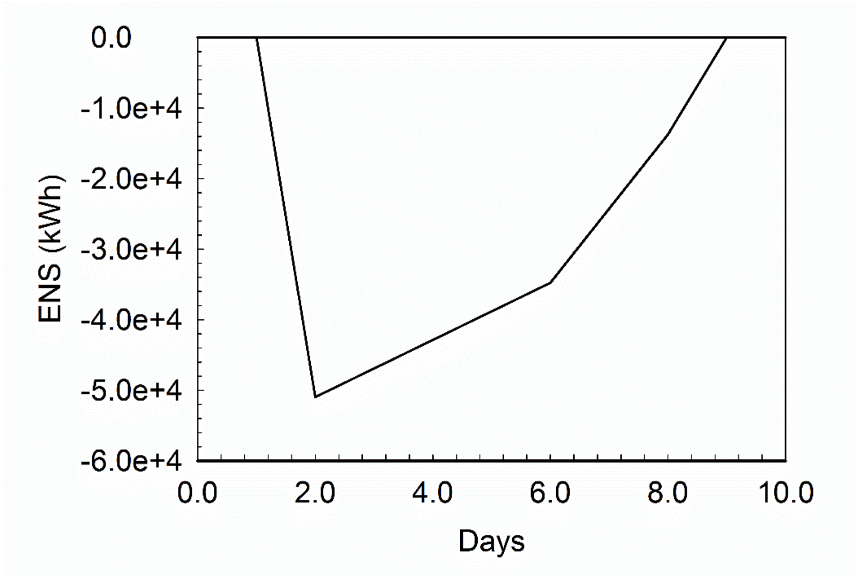


Figure 3-44 ENS per day

If the IRE index is focused on the single user, ENS stresses on the kWh lost. They highlight the same problems, but the last one allows second evaluations of the economic costs of a blackout. The weak point of this index is the lack of information on the damages size. The same results could be given by only big industrial substation or from ten of residential buses.

A new evaluation of the system resilience could be done with the GRE index (Figure 3-45). As in the previous cases, the shape of the function and the area under the curve represents the resilience. In this case the Trr parameter is equal to 0.57 because three classes of transformers are used and *AltPath* and *Gen* are both unitary because all the feeders are linked each other and in the region are assumed available temporary generators.

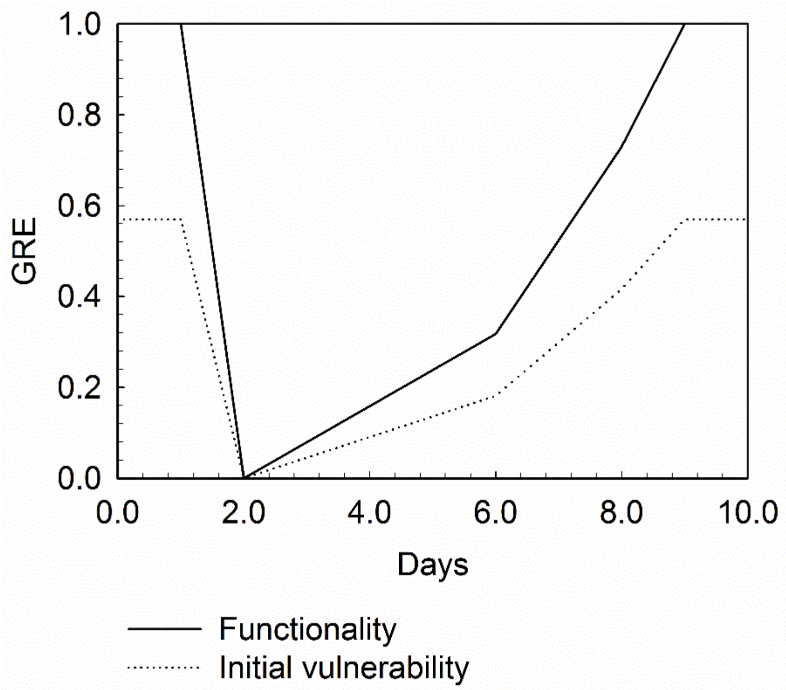


Figure 3-45 GRE Index

The GRE Index embodies the real definition of resilience and it can be represented in two ways. The continuous line is the index normalized to the initial conditions and it portrays the network functionality, according to the classical definition of resilience. The dashed line defines the starting conditions of the network due to its components. Two grids could have the same losses in terms of functionality but starting from different initial conditions highlighted by the dashed line. Differences like those can lead to different improvements in the grid resilience.

Moreover the scenario, in this case, is evaluated under the condition of possible temporary restoration thanks to alternative electricity paths or generators use. By the way, the curve is plotted to highlights the worst case and further studies could be conducted to define the impact of those improvements on the plot. Due to the failure of the entire grid the results of the three indices are coherent.

As it has been shown, a week is necessary for the complete restoration and this implying a huge loss of power. For an assignment of 4 kWh per day per user, the total amount for a district of the Ideal City, as the Crocetta case, consists in about 0.3 GWh. Considering the typical single-band price of 0.065€/kWh, the economic losses amount over 20,000 €. Accounting the repairs costs, losses further increase.

As reported in Figure 3-46, for the whole network failure, the total amount of costs for the transformers consists of 3.85 million euros. Additionally, the cost could increase if the ENS costs are taken in account. Figure 3-46 is obtained using the repair cost of transformers related to their quantities in Figure 3-42.

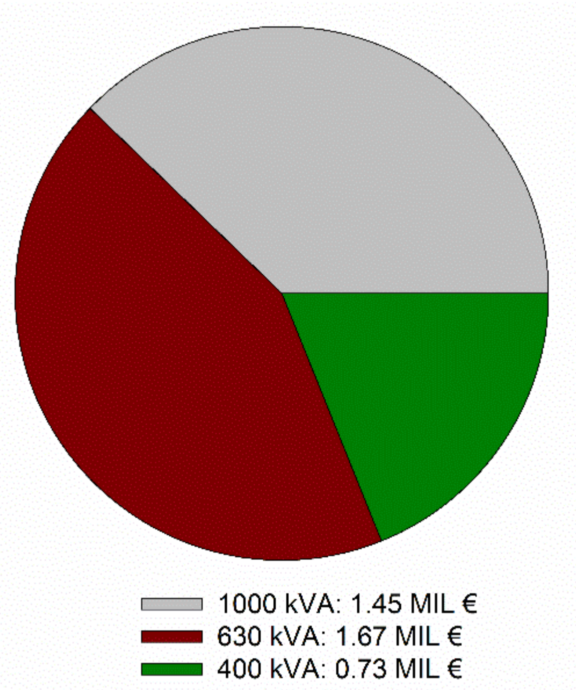


Figure 3-46 Transformers repair costs repartition

To improve network resilience, it may be useful to employ substations specifically designed for seismic conditions. Indeed, they are characterized by different fragility curves (Figure 3-47) with respect to the standard case in Figure 3-40. Fixing 0.5g PGA, the standard case defines about 90% probability of failure while the seismic case 50%. So, an essential difference can be highlighted.

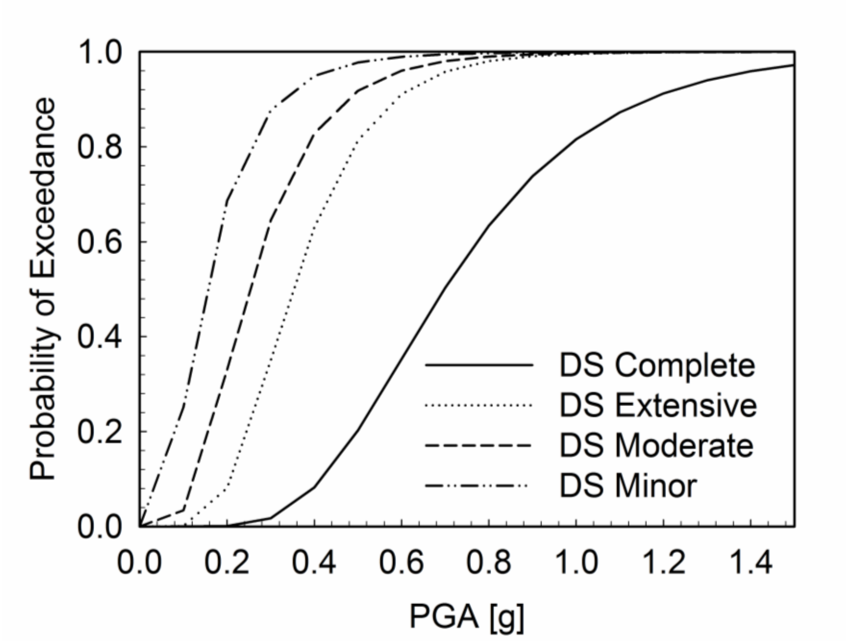


Figure 3-47 Fragility curves for medium voltage substations with seismic components

Finally, the networks interdependency has to be taken into account following the approach developed by Cimellaro et al. (Cimellaro 2016). The fragility of electrical components is connected to failure's probability of buildings system in the district, where substations are installed. Besides, the electric network failure itself induces a series of cascading effects, as summarized in the scheme of Figure 3-48.

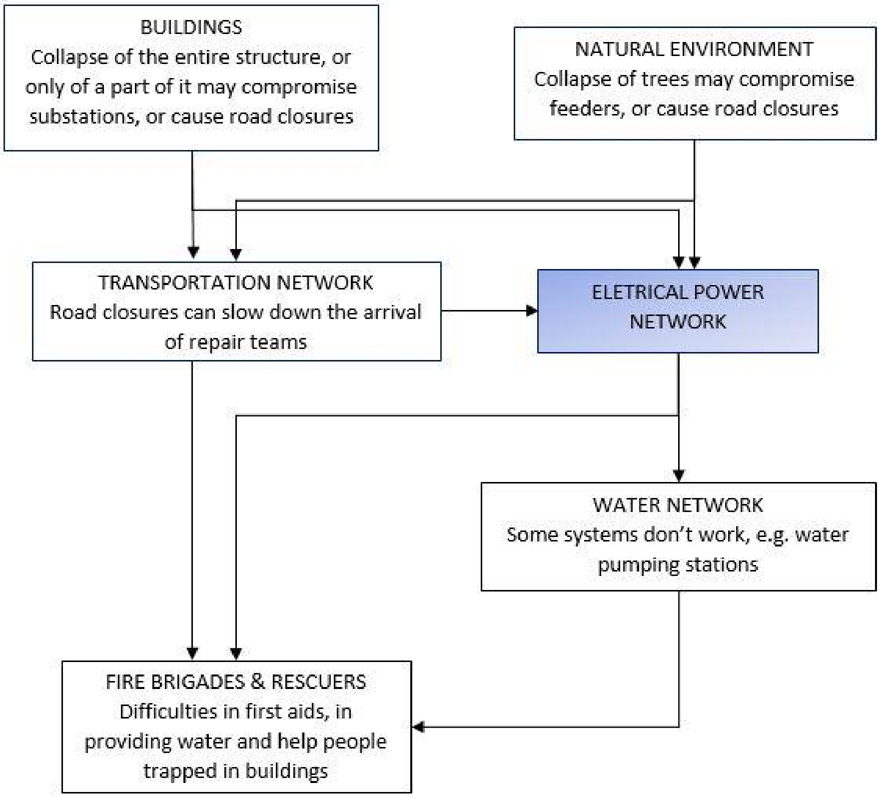


Figure 3-48 Indirect fragilities and cascading effects triggered by blackouts and power reductions

This Ideal City research team (Cimellaro 2016, Cimellaro 2017, Zamani Noori 2017) is deepening the cascading effects at the urban scale, creating a macroscale model through finite element (FE) analysis of buildings structures, debris and through connectivity matrices of the networks nodes.

This is the reason why the Density Designed Method is the approach chosen as the main one, it is the most suitable with this layer-based city scale simulation.

3.4.4 Second approach: Density Designed Network, Fragility & Resilience

With the Density Design Method the entire city is modelled, and a precise scenario will be applied to grid. First, as in the previous case, the network fragility must be defined.

In the described network, each substation is assigned uniquely to the closest buildings (Figure 3-49). Using the information about the electricity supplied to each user, it is possible to apply a deterministic seismic scenario and to analyse the results on the power network.

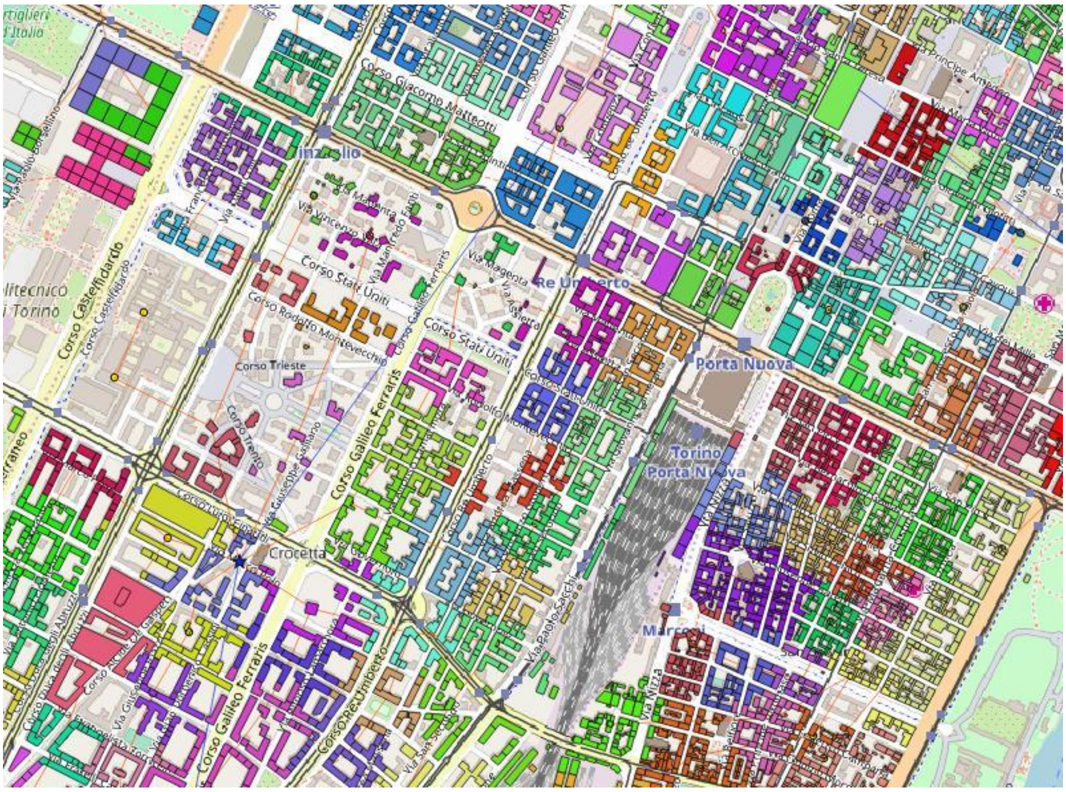


Figure 3-49 Assignation substations-buildings. Each colour identifies a different supplier

The fragility of the network is considered looking at the problem with a city-scale approach, so it is not more resumed in the intrinsic fragility of each component. If a building where a substation is installed collapses, there is the failure of the equipment there present. This is the most common failure of electrical components referring to literature (Celentano 2017), as shown in Figure 3-50 and Figure 3-51.

Figure 3-50 Substation building collapsed in the August 24, 2016 Earthquake in Rieti, Italy (Celentano 2017)

Figure 3-51 Internal detail of a substation building collapsed in the August 24, 2016 Earthquake in Rieti, Italy (Celentano 2017)

The substations fragility is linked to the buildings one. According to this rule, damages in the built environment are estimated using the resilience assessment tool developed in Politecnico di Torino (Marasco 2017). Assuming a certain scenario, the non-linear response of a multi degree of freedom for each building is considered, evaluating the post-elastic behaviour and over-strength factor associated. Moreover, a Monte Carlo Simulations is applied to take in account uncertainties related to geometry and mechanical properties (Marasco 2017, Zamani Noori 2017).

The earthquake used for this simulation is the 1979 Norcia Earthquake. This event occurred in the centre of Italy on September 19, 1979 and it had a 5.83 M_w (Moment Magnitude). In that case only few people died but it had huge consequences on the built environment, in particular on the great artistic heritage of that zone. In Figure 3-52 in red are highlighted the buildings damaged after the earthquake simulation.

Figure 3-52 Turin buildings damaged after Norcia Earthquake (details of the city centre)

Running the simulation are identified the buildings with a damage state “complete” and “extensive”, and the substations present in part of them are considered failed, in total 240 over 1274 (Figures 3-53 and 3-54).

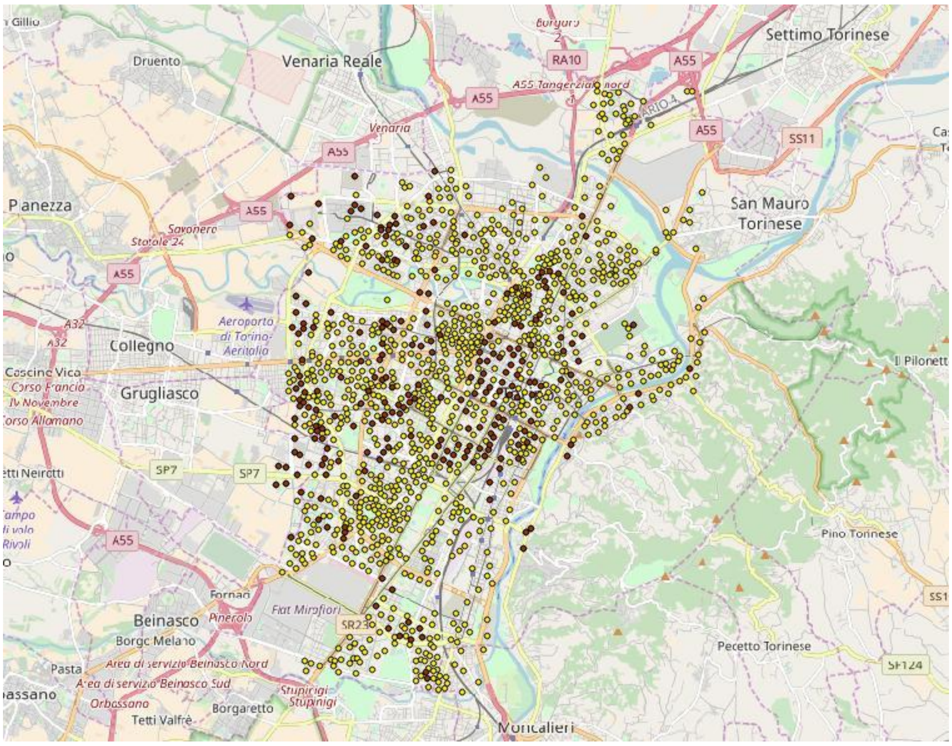


Figure 3-53 Distribution substations damaged after Norcia Earthquake

Figure 3-54 Distribution substations damaged after Norcia Earthquake (details of the city centre)

Referring to the assignation substation-building previously defined, at the end of the study the portion of the city (4815 buildings, 20,6% of the total amount) without energy supply is identified (Figure 3-55).

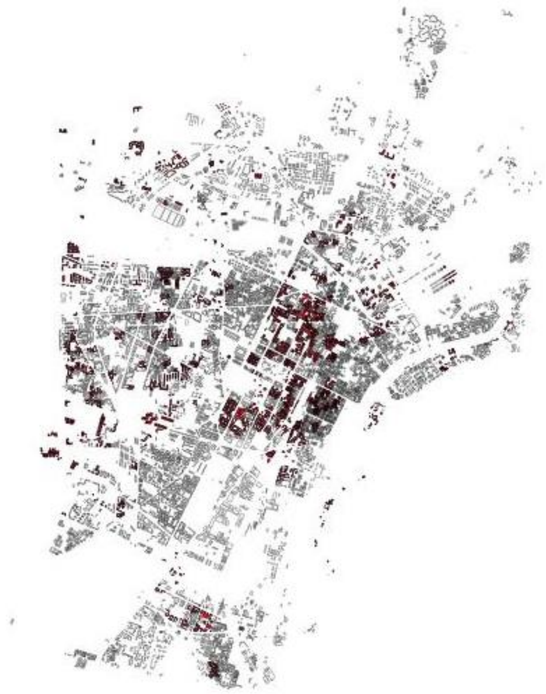


Figure 3-55 Buildings without energy supply

The resilience of the network designed with the Density Design Method is analysed with the same parameters of the one realized with the Similarities Design Method.

The substations recovery time is determined referring again to the data available for transformers, assuming those as the main component (FEMA 2016).

Moreover, using these hypothesis, the resilience index suggested by Italian Electricity Authority (The Italian National Authority for Electricity Gas Water and Wastes 2017) is evaluated (figure 3-56).

Note that all graphs start with a plateau to evaluate the initial condition of 100% functionality and then the event is considered to occur between hypothetical days 1 and 2 of the simulation (Figure 3-56). After these 24 hours, the action of the disservice causes is considered exhausted and the assessment of the consequences can be started. In these plots, a polyline is used due to the event discretization.

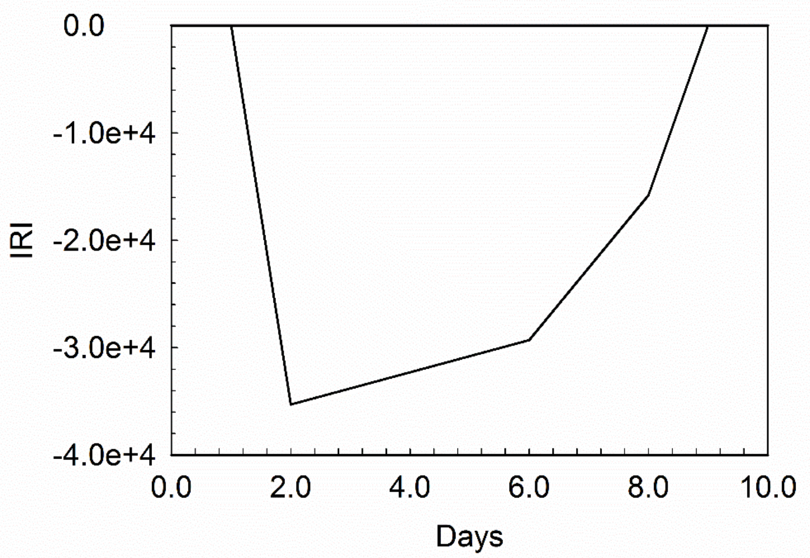


Figure 3-56 IRI Index

The focus is on the users disabled, and in this case, they are 17,650 out of 960,500 customers served. As in the previous scenario, the area under the IRI vs Days curve is the IRE evaluation and this plot highlights the long restoration times of the substations. Nevertheless here, after four days, almost the 50% of the grid is again in function. So, the network is sensitive to a huge risk of failure, but it is more resilient due to a better composition of the equipment.

A second evaluation of the damages is performed referring to the energy not supplied (ENS) before the network restoration (figure 3-57).

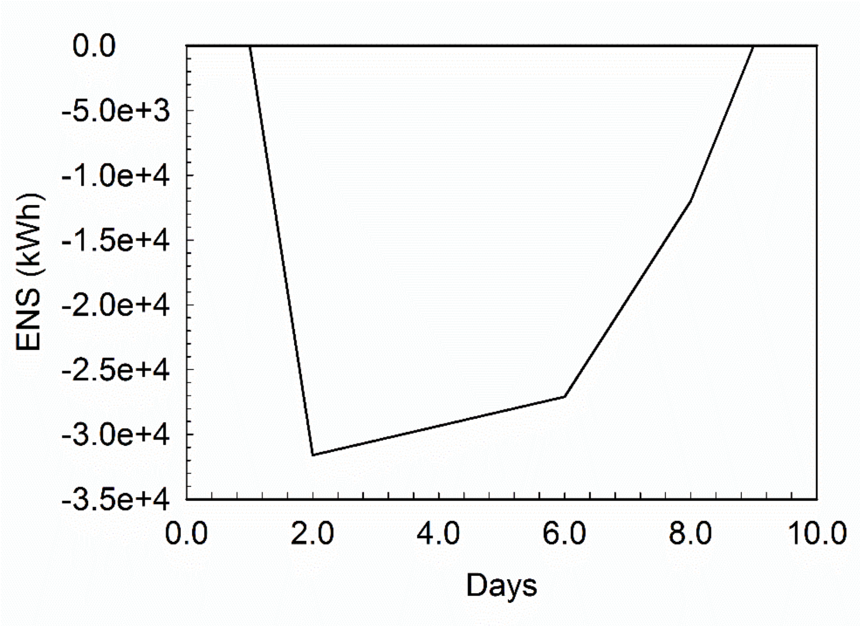


Figure 3-57 ENS per day

The ENS points out the kWh lost due to the power outage. As described by the IRE index this network is more resilient and this represents an advantage also from the economic point of view because the losses are smaller. The cost consequences are later described in this paragraph.

This grid presents a good robustness but regarding the rapidity and the resourcefulness, there is a long way to go. These aspects are not enough highlighted with this parameter.

A new evaluation of the system resilience could be done with the GRE index (Figure 3-58). As in the previous cases, the shape of the function and the area under the curve represents the resilience. In this case the Trr parameter is equal to 0.57 because three classes of transformers are used and *AltPath* and *Gen* are both unitary because all the feeders are linked each other and in the region are assumed available temporary generators.

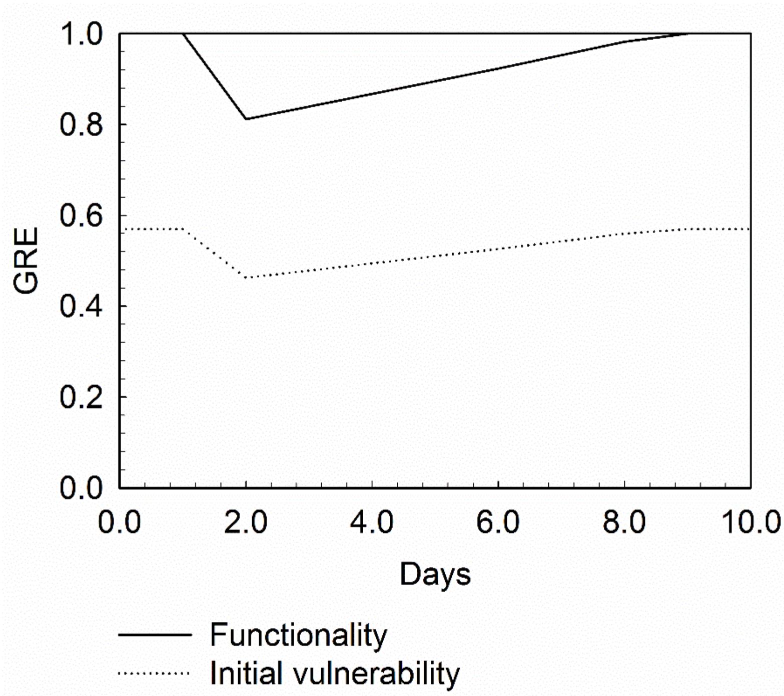


Figure 3-58 GRE Index

The GRE Index embodies the real definition of resilience and it can be represented in two ways. The continuous line is the index normalized to the initial conditions and it portrays the network functionality, according to the classical definition of resilience. The dashed line defines the starting conditions of the network due to its components. Two grids could have the same losses in terms of functionality but starting from different initial conditions highlighted by the dashed line. Differences like those can lead to different improvements in the grid resilience.

Moreover the plot highlights the grid robustness and makes in evidence the lack of rapidity in the restoration process. It means that more information from the repairs evaluation side must be collected, and more efforts have to be made to guarantee an appropriate and quick restoration of the substations. So, the idea to more study the use of temporary solutions, such as alternative electricity paths and generators, is right and it must be followed with further researches and case-studies.

The energy not supplied represent for city planners and public utilities not only a huge direct cost but also indirectly, e.g. the cost related to electrical components replacement (figure 3-59), (FEMA 2016). Figure 3-53 is obtained using the repair cost of transformers related to their quantities in Figure 3-42.

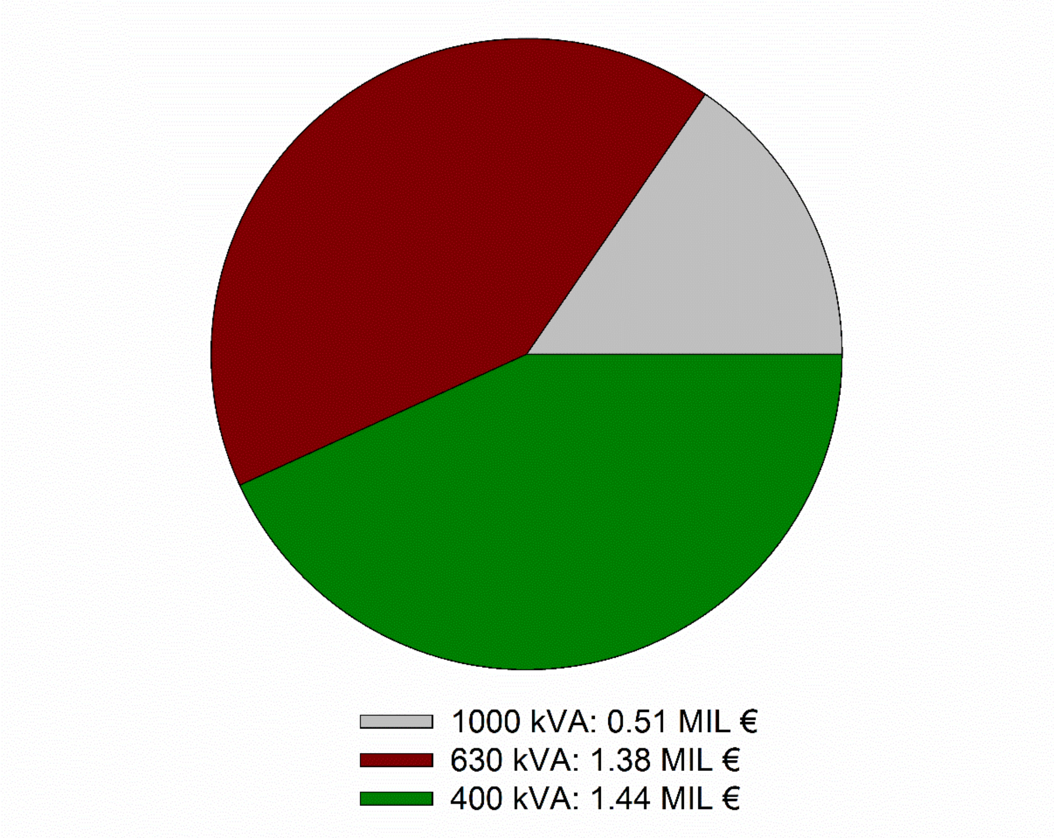
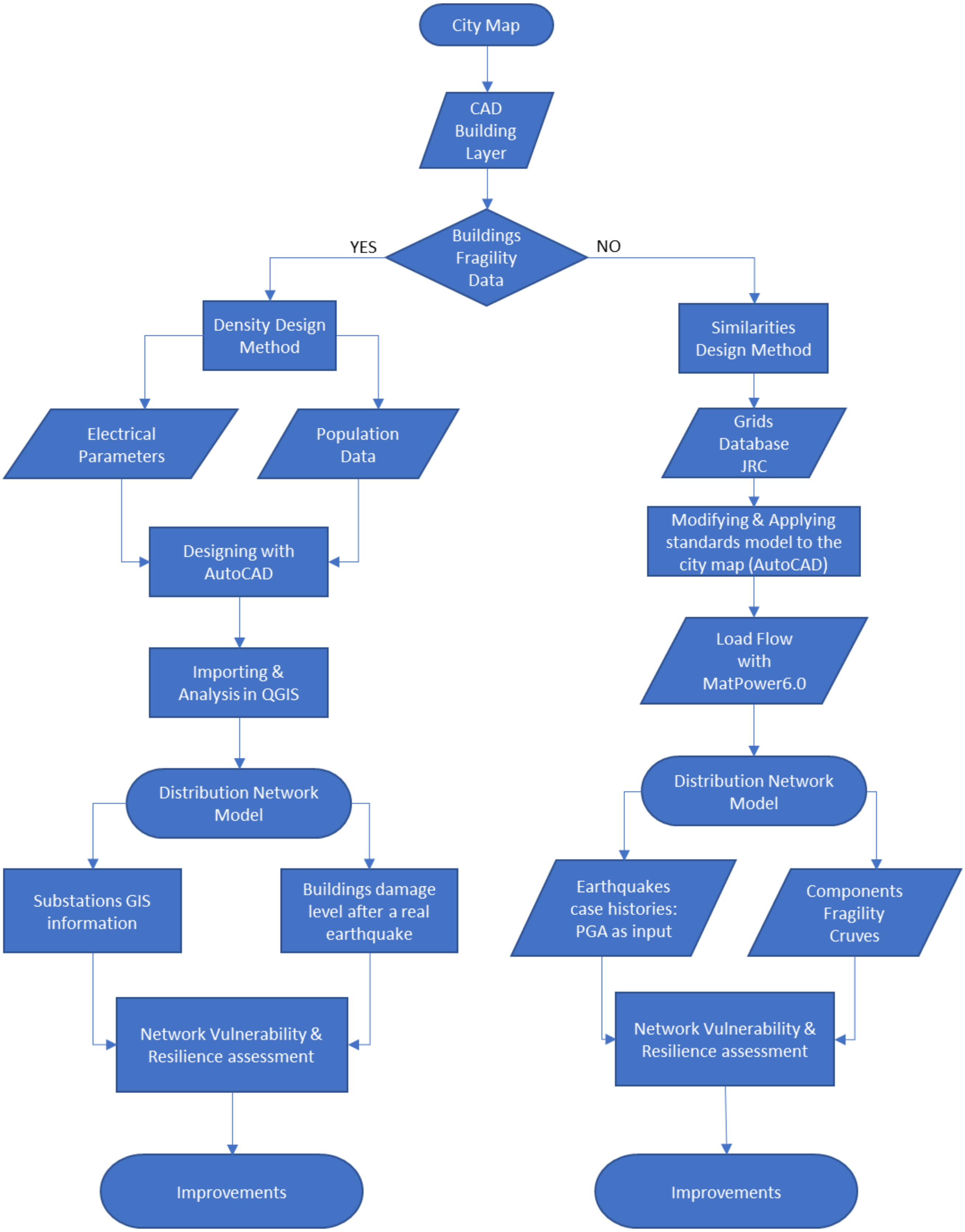


Figure 3-59 Transformers repair cost repartition

3.5 Comments

In this chapter, two methodologies are presented, and they could be applied in different cases. To define the boundaries of the applicability of these approaches a flow charts is provided.


City Map
CAD Building Layer
Buildings Fragility Data
YES
NO
Density Design Method
Similarities Design Method
Electrical Parameters
Population Data
Grids Database JRC
Designing with AutoCAD
Modifying & Applying standards model to the city map (AutoCAD)
Importing & Analysis in QGIS
Load Flow with MatPower6.0
Distribution Network Model
Distribution Network Model
Substations GIS information
Buildings damage level after a real earthquake
Earthquakes case histories: PGA as input
Components Fragility Cruves
Network Vulnerability & Resilience assessment
Network Vulnerability & Resilience assessment
Improvements
Improvements

In this thesis, some indices to assess the performance of a distribution power network are proposed and a realistic case study is created to compare them. First, the approach starts with the city map of the case study. Only starting from a precise topology some evaluations can be done. Moreover, on the map, the buildings must be represented with CAD and information about their fragility collected.

At this point, there are two options. If this information is not yet available, a simplified method can be used. Otherwise, a more detailed approach is possible.

With the first approach, called Similarities Designed Method, a grid from a renowned database is selected and then is applied neighbourhood by neighbourhood adding or deleting some buses, checking the load flow with an appropriate tool. Now the indices can be evaluated using a set of PGAs and the components fragility curves.

With the second approach, called Density Designed Method, the grid is designed from zero using load density and population density data. This information is then inputted on AutoCAD and geo-referenced in QGIS. The components fragility in this method is the assumed the same of the buildings where this equipment is installed. Now the indices can be evaluated using a real case history.

Please note that the simplified method is the first approach to use, but not simply a first attempt. When the Density Designed Method is applied, the improvements in the buildings vulnerability can be done. If the theoretical earthquake-proof condition is reached, the assumption of the same fragility between electrical equipment and buildings is no more valid. Under these hypotheses, the main role is now played by the intrinsic fragility of the power network. This can be still evaluated with the first approach, updating the fragility curves for medium voltage substations with the ones associated to seismic components.

In conclusion, the two methods are not alternative but complementary, and by making a civil engineering correlation with the definition of a collapse multiplier, also in this field, the most unfavourable evaluation must be considered. Based on this estimate, the city planner must make decisions and improve the resilience of its distribution network.

3.6 Annexes

To run these analyses the software used are the well know AutoCAD for the design and positioning of the buses in the buildings city map and QGIS, also known as Quantum GIS, that is an open source software for geographic information system.

Developed since 2002 but released for the first time only 2009, it is written in C++ and it includes different dependencies such as Graphic Environment Operating System (GEOS), Geospatial Data Abstraction Library (GDAL) and Geographic Resources Analysis Support System (GRASS GIS).

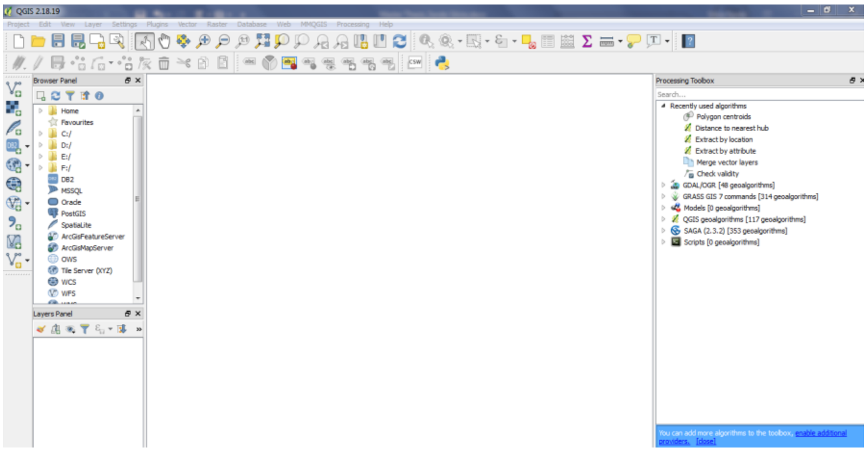


Figure 3-60 QGIS 2.18 opening window

The release used for this thesis is the 2.18 LTR, also known as “Las Palmas”, that is based on Qt4 (fourth release of Qt, a cross-platform application framework for graphical user interfaces and applications) and Python2.7 (general purpose programming language). This choice was taken because on the download website this version is suggested as the most stable and used in relevant applications.

Recently, QGIS or similar software have been applied in a lot of applications, not only in the civil engineering field. For example, the public administration of Austrian state of Vorarlberg, and the Swiss cantons of Glarus and Solothurn have introduced this application in their work activities.

In the resilience field and especially referring to power networks, the use of this software is quite new and for this reason the relevant commands and functions used to perform these analyses now are explained:

- *Import a DXF:* QGIS is a very opened software able to communicate with different other applications, such as all the Autodesk products, and with other software the work with ShapeFiles like the commercial ArcGis

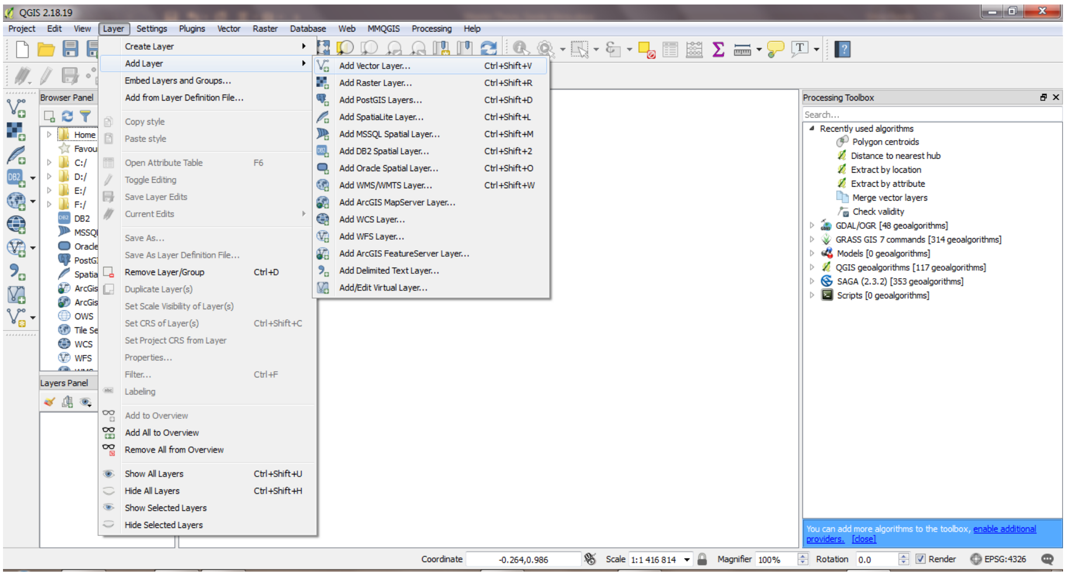


Figure 3-61 How to import DXF in QGIS

- *Characterize each layer:* in QGIS it is possible to apply styles of each layer, categorizing different elements of the same layer according to specific properties. Furthermore, each element is defined with several attributes that could elaborated and modified using mathematical and logical functions. These attributes could be imported and exported as .xml files, easily readable with Excel.

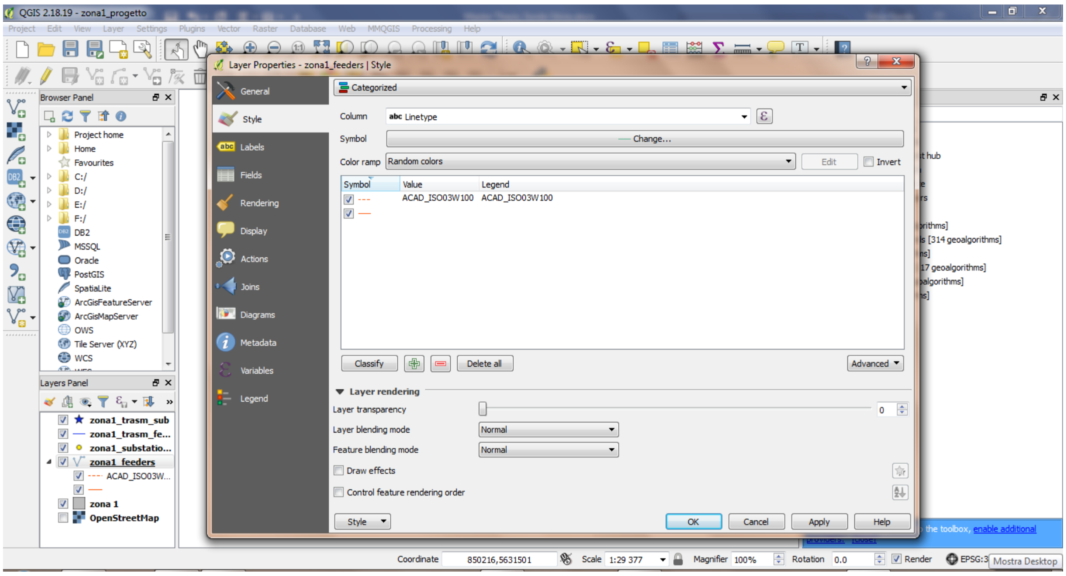


Figure 3-62 QGIS Layer Properties window

- *Geometry tools:* geometric information, such as polygonal centroids, joining or exploding polygons into lines, extracting nodes or operate Delaunay triangulation are all actions simply performable using the proper commands.

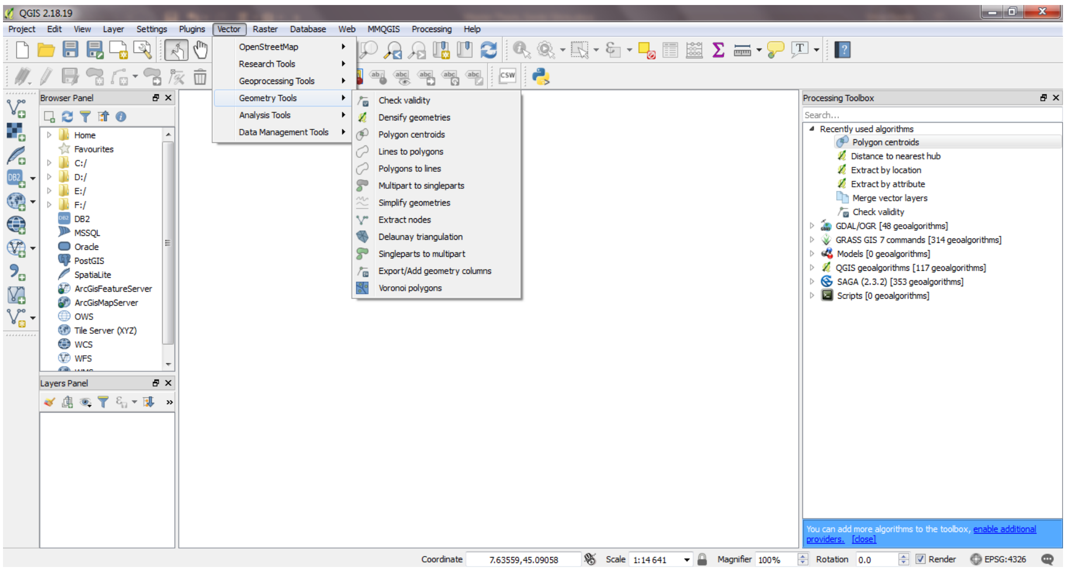


Figure 3-63 QGIS Geometry tools window

- *Analysis and Processing tools:* in QGIS are implemented functions to calculate important relationships such as “extract by locations”, “extract by attribute”, or “distance to nearest hub”. Basic statistics relations and distance matrices could be evaluated with dedicated commands.

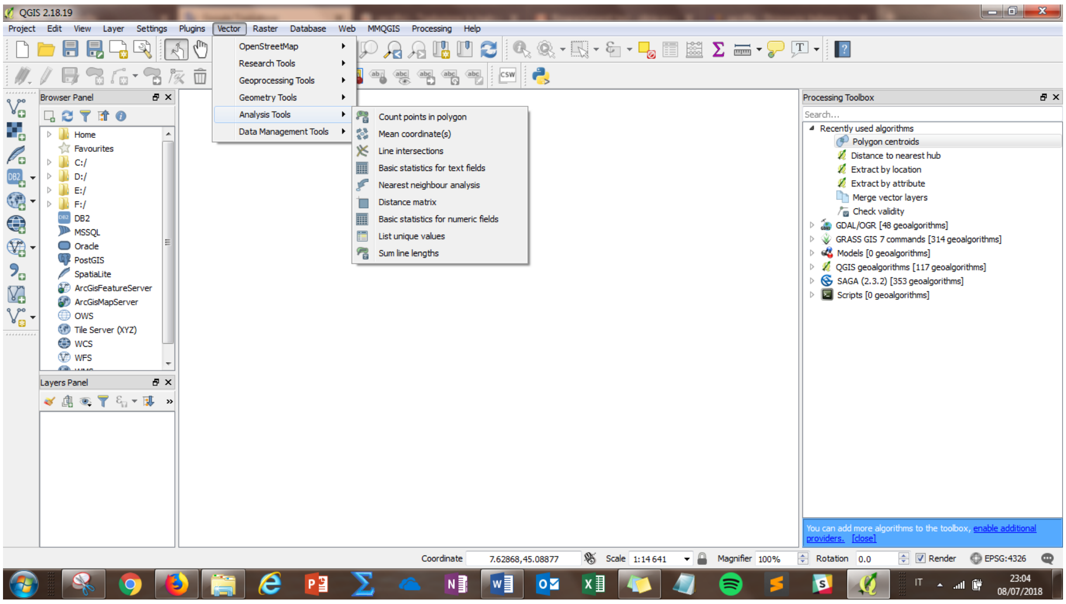


Figure 3-64 QGIS Analysis tool window

4 Conclusions

This thesis dealt with the resilience of critical infrastructures, describing the power network of a virtual city inspired by Turin. In this project called Ideal City, all the infrastructures are modelled and connected.

In addition to that, also the human behaviour in emergency conditions is under investigations and therefore an introduction to an Agent-Based Model is presented. An agent is created, and his choices are shaped according to the traffic data taken from Google. All the steps for the element creation and movements made respecting the different traffic conditions are shown and in detail described in the annexes.

The main goal of this study is to assess the performance of a distribution power network under emergency conditions. The effects of the recent biggest blackouts led the Italian Government to the definition of new parameters to describe the grid's vulnerability, but more could be still done in this field. This is the reason why the classic index Energy Not Supplied and the new Index of REsilience are tested but a new parameter called Grid REsilience is also introduced.

No real data were available and to run these tests a realistic case study is created. So, two design methodologies are introduced and applied.

The Similarities Design Method allows defining a compatible grid from a reliable set when buildings fragility data are not available and different scenarios need to be quickly tested. This is a powerful tool to determine the general scheme a power network.

The Density Design Method leads to complete evaluation of a power grid starting from its electrical parameters and according to the real number of users. Using the population and load density (from these input data derives the method's name) and respecting the electrical engineering constraints on the feeder's lengths and buses types, the Ideal City distribution grid is modelled neighbourhood by neighbourhood. The results are shown and compared to the IRETI data with a very good match.

The first approach is more focused on the intrinsic fragility of the power network, while the second one highlights the strong relationship between buildings and electrical equipment installed. The two methods are complementary and the power of this double approach is that in the end the worst conditions for the grid must be considered and, on those, solutions must be implemented.

However, to evaluate the worst-case, indices are required. So, in the end, the three indices are calculated for different scenarios and compared. The analysis shows that the ENS points out simply the economic losses in terms of GWh lost, while the IRE is focused on effects on the costumers. From two different point of view, they describe the same concepts. On the other hand, the GRE index embodies the concept of resilience, giving an assessment of the grid in terms of rapidity, robustness, redundancy and resourcefulness. As matter of fact, in the Norcia Earthquake scenario with the GRE vs Days plot, it is clear how an apparently robust power network could be affected by huge losses if the restoration operations are not fast. The little drop immediately after the event is followed by a smooth inclination of the function that depicts the longer repairs time due to the use of three classes of transformers.

Nevertheless, in the definition of new indices, further improvements can be done. First, the grid design could be improved by adding more electrical parameters to allow in the future a load flow analysis of the entire grid, hoping in a collaboration with the local power companies. Furthermore, the GRE index could be better calibrated by deepening the redundancy and resourcefulness fields. Tests and scenarios where these aspects of resilience are involved could add information to the general model.

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