A METHODOLOGY TO EVALUATE STRATEGIC IMPORTANCE OF BRIDGES AND TUNNELS CONSIDERING SEISMIC VULNERABILITY: APPLICATION TO LISBON

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Abstract

This work presents a model (MAGIE) to assess the strategic importance of bridges and tunnels in the Lisbon road network. The main goal of this model is to develop a prioritization method for the formulation and implementation of policies to prevent and repair seismic damages in bridges and tunnels.

Introduction

The occurrence of strong earthquakes in urban areas causes problems related not only with human losses, but also with the damage of several kinds of infrastructures.

Bridges and tunnels are critical components within the transportation systems. The loss of functionality of these structures immediately after seismic occurrence demonstrates their importance in all aspects related to the emergency response process. Immediately after the seismic occurrence, until the reposition of normality it is necessary to find alternative roads with a consequent loss of serviceability of the transportation systems. Therefore, it is important to develop measures to help to mitigate possible risks and consequences of seismic damage on existing bridges and tunnels.

The process of intervention on bridges and tunnels such as the application of retrofitting measures and upgrading to current design codes, are extremely costly and time consuming [1]. On the other hand, all the governmental departments responsible by these structures have limited economic and human resources to perform these tasks. On a preliminary stage, the use of prioritization methods that allow to quickly identify and rank the structures that need to be retrofitted is extremely important [2].

In this paper, a multicriteria evaluation model (MAGIE) to assess the strategic importance of bridges and tunnels on a road network, considering the perspective of a Civil Protection

Department is presented [3]. The main goal of this model is to develop a prioritization method for the formulation and implementation of policies to prevent and repair seismic damages.

The north area of Lisbon was used to test the model developed. This zone was chosen because of its seismological characteristics and the considerable number of bridges and tunnels present on its road network.

Conceptual Evaluation Model

In the last decades, several studies have been developed to facilitate the formulation of retrofitting programs. These studies can be classified in three groups:

- The first group of such studies is based on cost-benefit analysis. They intend to support the decision of retrofit or implement a new structure [4].
- The second group is based on linear regression models. On these studies, the level of damage is correlated with the structural attributes of the infrastructure and local geological characteristics to determine the safety level of the bridge or tunnel analyzed [5]. The selection of structures to retrofit is based on the results of the model.
- Finally, the third group includes multicriteria models that aggregate different points of view, which contribute to the vulnerability of the structure. These models differ on the objectives and the aggregation methods used [6]. The most well known examples of this kind of evaluation are the models developed by the California Department of Transportation, Applied Technology Council and by the Japanese Building Ministry [7].

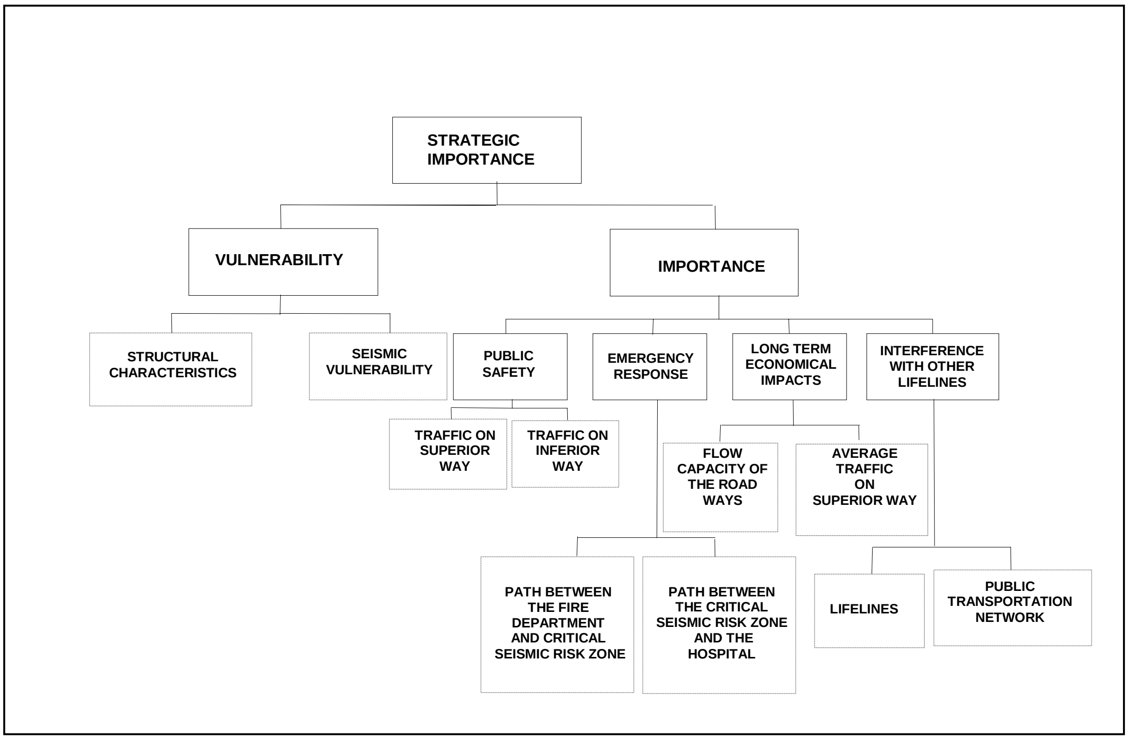

Figure 1: *Fundamental Points of View* considered on the MAGIE model

The development of the evaluation model (MAGIE) presented in this paper, followed the steps defined in a multicriteria analysis. In the first phase, the problem and the specific decision context were described and explained. Afterwards, the structuring and framing phase were developed. This phase included the definition of objectives and relevant components for the decision context. This phase should progressively lead to the identification of *Fundamental Points of View* (*FPV*), and to their clear description. The following step corresponded to the description of the evaluation model, which included the definition process of value functions and of scaling constants (weights).

During the structuring MAGIE phase two "*Areas of Concern*" had been identified **(Figure 1):**

- **"*Vulnerability*"** depends of the inherent characteristics of the structures and on local seismicity. In other words "vulnerability" is a function of the structural properties of the bridge or tunnel and the site hazard. Thus the *Elementary Point of View* (*EPV*) considered are the "*Seismological Behavior*" and "*Structural Vulnerability*".

- **"*Importance*",** which depends on the factors that contribute to the *Strategic Importance*. During the structuring process four *FPV*: had been identified: "*Public Safety*", "*Emergency Response*" (immediately after the earthquake), "*Long Term Economic Impacts*" (during the reposition of normality) and "*Interference with other Lifelines*".

To evaluate the different *FPV,* a *descriptor* was associated to each one of them. A *descriptor* is an ordered set of plausible *impact levels* in terms of a *FPV*, intended to serve as a basis to describe, as much as possible objectively, the impacts of alternatives (bridges and tunnels on this case) [8]. **Table 1** presents a summary of the *descriptors* used within the MAGIE model.

Table 1:*Descriptors* of the *Fundamental Points of View* included in the MAGIE Model

Fundamental Point of View	**Descriptors of Impacts**
PV1 (Vulnerability)	Structural Vulnerability in function of the local seismic local vulnerability (qualitative scale)
PV2 (Public Safety)	Number of people that cross a bridge or tunnel by minute in the morning rush hour period (person/minute)
PV3 (Emergency Response)	Lost of efficiency of the preferential routes used with Emergency purposes (Hours)
PV4 (Long Term Economical Impacts)	Lost working days due to the loss of functionality of one bridge or tunnel. (equiv. Lost working days/day)
PV5 (Interference with other lifelines)	Number of interference's with other lifelines (qualitative scale)

Finally, to obtain an overall aggregation of the different value functions an additive model was used. The cardinal function was defined using the MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) approach, to evaluate the "Strategic Importance" on a global way. One advantage of this approach is the fact that it is usually well understood by the different decision-makers involved on the decision-making process [8,9].

The necessary scaling factors were also obtained with the help of the MACBETH approach.

Scales within MACBETH are defined according to the concept of difference of attractiveness of the different actions. Let $S = \{S_n, S_{n-1}, ..., S_1\}$ be a finite set of n stimuli- in this case n is the impact levels of a *FPV* descriptor. Based on judgements of an evaluator *E* about the attractiveness of the elements of *S*, MACBETH is an interactive approach to guide the construction of an interval scale *v* on *S*, that is a numerical scale v: $x \varepsilon S \to v(x) \varepsilon \Re$ for which the idea of difference of attractiveness is meaningful. The approach to derive such a scale consist of:

- in a first stage, to use a very simple questioning procedure involving only two stimuli procedure involving only two stimuli in each question, and to assign a real number *v*(*x*) to each stimulus *x* of *S* on the basis of straightforward measurement rules for quantifying the preference information given by *E*;

- in a second stage to discuss wit *E* about the cardinality of the scale *v* constructed in the first stage.

MACBETH questioning procedure consists in asking *E* to verbally judge the difference of attractiveness (diff. att.) between each two stimuli *x* and *y* of *S* (with *x* more attractive than *y*) choosing one of the following semantic categories: **C_1** - *very weak* diff. att, **C_2** - *weak* diff. att., **C_3** - *moderate* diff. att, **C_4** - *strong* diff. att., **C_5** - *very strong* diff. att. and **C_6** - *extreme* diff. att..

During this questioning process, the facilitator fills in matrix with the categorical judgements of *E*.

The final phase of the process of evaluation aims to aggregate every defined *FPV* in a unique value with an additive model:

$$V(c) = \sum_{j=1}^{n} k_j v_j(g_j(c))$$

Where:

V(c) = Overall value of structure c measuring its attractiveness in terms of strategic importance;

gj (c) = Impact of c in the *FPV*j;

vj (gj(c)) = partial value (attractiveness) of c in the jth *FPV*;

kj =scaling factor for the *FPV* j.

The determination of the scaling factors is also based on the MACBETH approach [8]. "Let $A^F = \{a^0, a^1, ..., a^j, ..., a^{10}\}$ be a reference set of ficticious bridges and tunnels where a^0 is a refrence set of ficticious structure with the plausible worst impacts levels in all *FPV*, and a^j (j=1,…,11) is a reference fictitious structure with the plausible best impacts in the jth *FPV* and the plausible worst impacts in all the other *FPV*. Of course, given the conditions above, V(a0)=0 and V(aj)=100.kj.

Formally, MACBETH questioning procedure for weighting the *FPV* consisted in asking the s:

- first, to compare all two reference structures a^j and al in A^F in terms of overall attractiveness;
- Second, to judge semantically the difference of overall attractiveness between any two references structures such that the first one is more attractive than the second one.

Case Study

The area chosen for the case study is located in the north part of Lisbon and includes a diversity of *Points of View* considered in the MAGIE model (**Figure 2**). This area includes different structures belonging to a diversity of typologies; a critical area of seismic risk, a main road and two infrastructures to support the emergency response. The transportation network included in the chosen area includes ten structures, eight of which belong exclusively to the road network while the other two are part of the train and the underground network. The critical area of seismic risk contained in the case study area was defined as such by the Lisbon Municipality Emergency Plan for Seismic Risk and it includes historical neighborhoods [10].

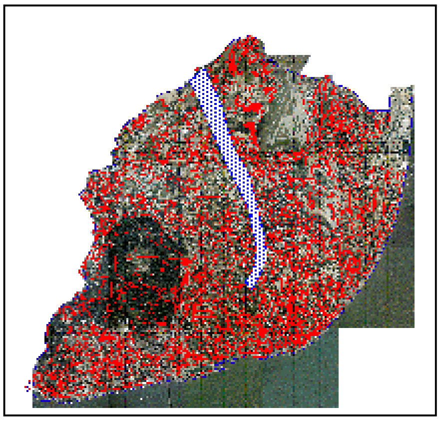

Figure 2 : Case study area

Concerning the emergency infrastructures, the chosen area is served by the Santa Maria Hospital, one of the highest capacity hospitals in the Lisbon area. The ambulance fleet used to rescue the victims in the case study area is located in the Av. Rio de Janeiro Fire Department. Within this case study, the optimal path between the Fire Department, the critical seismic area and the hospital was used to evaluate the efficiency of emergency operations.

The routes belonging to the primary network included in the study area connect the North of Lisbon suburban area and the Lisbon city center.

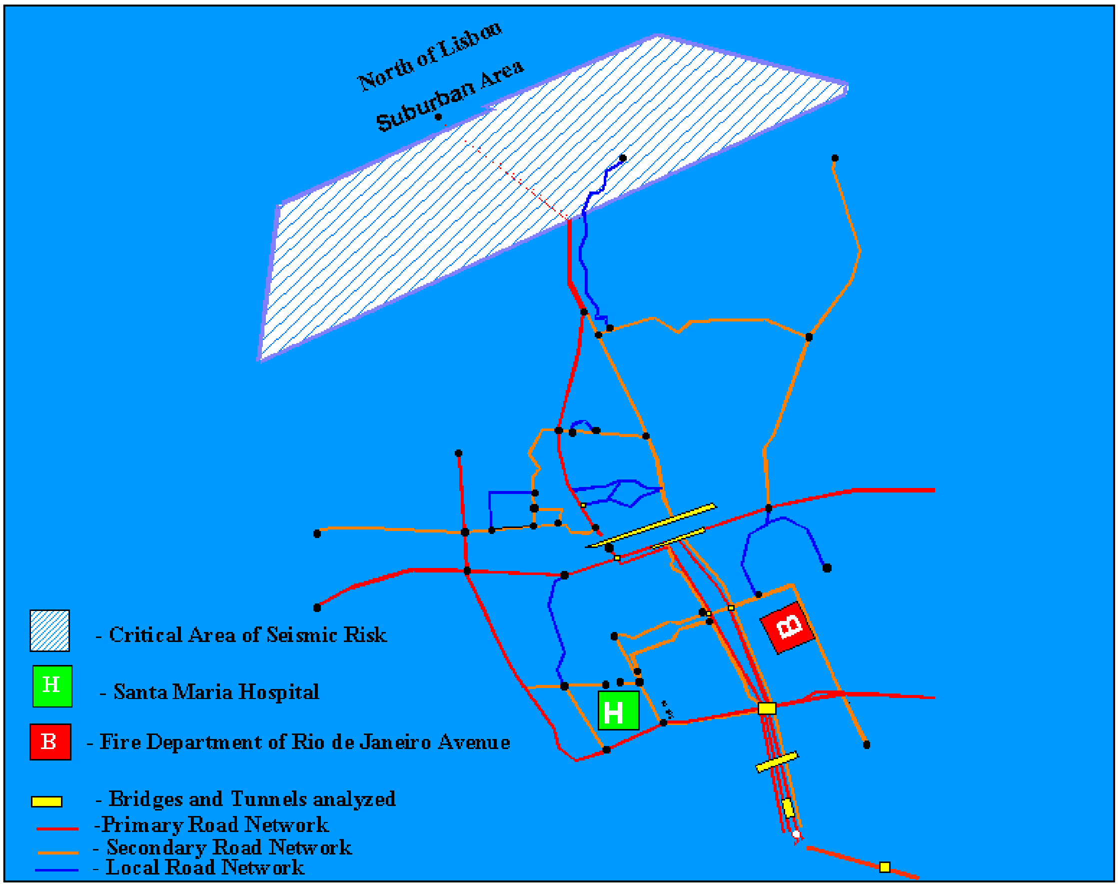

Figure 3: Characterization of the Area

A database containing information on the existing tunnels and bridges was developed as an auxiliary tool for the evaluation process. This database was structured in four tables that included the different characteristics related to the *Elementary Points of View* (*EPV*). The first table included a description of the relevant characteristics of the existing tunnels and bridges. The second table has stored data on local seismic vulnerability. The third table contained information on the "*importance*" area of concern. More specifically the information stored in the third table incorporated: the number of: the roads on and under the bridges, the road network hierarchy, the number of lanes, the number of ways, the traffic average values and the structure interconnection with lifelines. Finally, the fourth table included images of each bridge and tunnel, which intended to facilitate the classification process.

The determination process of the level of impact for each *FPV*, concerning the 10 bridges and tunnels included in the case study area (Figure 3), was the following:

Vulnerability

To classify the bridges and tunnels according to their vulnerability it was necessary to perform a set of chained queries to the database. The first query selected the information referred to the different bridges and tunnels included in the study area. Afterwards, a new query about the age and structural characteristics of the already selected registers was performed. This procedure allowed to aggregate the different actions according to the established classes while the impact levels were defined.

After the classification of all actions, they were matched with each attribute of the Vulnerability Characteristics table. This process intended to relate the tunnels and bridges classes obtained to the *EPV* Seismic Vulnerability, through the use of provisory fragility curves conceived for this purpose. It was then possible to get the level of impact of the Vulnerability descriptor.

Importance

Public Safety: To define the level of impact of the public safety descriptor the average traffic value of the roads on and under the bridges had been used. Through the use of the traffic values presented in the Lisbon Municipality Master Plan it was possible to estimate an average daily traffic value for the period between 7 a.m. and 9 p.m.. Assuming that the traffic distribution was uniform along the time period considered, it was possible to determine the number of vehicles per minute that cross the bridge. Additionally, assuming a specific vehicle occupancy rate it was then possible to estimate a value for the "public safety" impact level (**Table 2**)

Emergency Response: The determination of the impact level for the *FPV* "Emergency response" begins with the identification of the response resources that can be activated if an accident occurs within the critical seismic risk area. It is then possible to define the optimal path in a normal situation, in other words, with all the structures in an operational stage. The next step to define the *FPV* "Emergency response" is to define the optimal paths, considering that simultaneously there is only one of the structures that is not operational.

Using the outputs of the damage estimation model an average number of victims was estimated for the critical area for a scenario with an epicenter in the lower Tagus valley and a magnitude of 6.5 for the time period between 9 a.m. and 6 p.m.[10]. This value was multiplied by the time lost in the emergency response differential to allow the descriptor to reflect the number of routes necessary to perform the emergency response process. This process allowed to obtain the desired level of impact in other words the total hours needed to carry the all the victims from the critical area to the hospital. (**Table 2**)

Long Term Economic Impacts: The level of impact for each action within the "Local Economic Impacts" descriptor has been calculated based on the loss of serviceability of the major roads within the study area. The most efficient alternative routes were calculated for each bridge. The alternative routes were penalized with speed constrains and loss of efficiency. The penalty was a function of the number of lane decrease.

The total number of hours of delay was calculated considering the traffic values and the increase in distance and congestion on the routes established as alternative [11]. Assuming the number of working days as a measuring unit, it is possible to determine a value for the working time lost per day due to the loss of functionality of one bridge or tunnel (**Table 2**).

Interference with Lifelines: The development of *descriptors* for this level of impact was based on site inspection, when the interference with water, power, gas supply and telecommunication networks was identified. Additionally, information on the public transportation network (such as train networks and Bus dedicated lanes) was also included. (**Table 2**).

Table 2: Impact Levels obtained for each of the *Fundamental Points of View* considered in the model

Structure ID	**Vulnerability**	**Public Safety** ers../min	**Emergency Response** Time	**Long Term Economical Impacts** Lost Days	**Interference with other lifelines**
41	Recoverable	198	0 h : 00 m	1829	With one lifeline
57	Recoverable	181	0 h : 00 m	344	With one lifeline
58	Examination Required	222	0 h : 00 m	512	With two lifelines
59	Examination Required	175	0 h : 00 m	515	Without interference
75	Recoverable	113	0 h : 30 m	1002	With one lifeline
76	Recoverable	231	1 h : 30 m	914	With one lifeline
77	Unserviceable	179	1 h : 00 m	179	Without interference
77’	Unserviceable	193	2 h : 00 m	300	With two lifelines
78	Recoverable	83	0 h : 00 m	100	With one lifeline
79	Recoverable	87	0 h : 00 m	100	With one lifeline

Table 3: Scaling Factors obtained for each of the *Fundamental Points of View* considered in the model

Fundamental Point’s of View	**Scaling Factors**
Emergency Response	26,76
Vulnerability	23,94
Public Safety	21,13
Interference with other life lines	14,08
Long Term Economical Impacts	14,08

The development of the different cardinal functions and the scaling factors have been calculated according to the above mentioned process using the MACBETH software.

The aggregated additive model was used, after the calculation of the scaling factors, to get the final results that allowed to rank the 10 structures studied. (**Table 4**)

Table 4: Outputs of the Evaluation of the Strategic Importance Level Model

Structure ID	Vulnerability	Importance	Global Value
41	10,29	61,1	**56,8**
57	10,29	81,7	**72,4**
58	17,00	71,5	**71,4**
59	17,00	86,1	**82,5**
75	10,29	78,3	**69,8**
76	10,29	60,5	**56,3**
77	0,00	81,6	**62,1**
77’	0,00	58,7	**44,6**
78	10,29	91,3	**79,7**
79	10,29	91,0	**79,5**

The model results showed that the structures classified with fewer points were the ones that were the most important for the system and therefore should have priority in the establishment of a detailed inspection program. Within the case study the bridge 77 with the global value of 44.6 was established as the top priority to start an inspection program.

Conclusions

Based on a multicriteria analysis, an evaluation model for the strategic importance of bridges and tunnels in Lisbon was developed. The benefits of using a multicriteria approach to support the resolution with high diversity of factors and high level of subjectivity are discussed in this paper.

In the case study presented in this paper the MACBETH model was used. This model differs from other multicriteria models described in the literature since it does not use utility functions and tradeoff value models to express the difference in attractivity among the *descriptors* level of impact and the scaling factors. The MACBETH approach has demonstrated to be a good tool for decision-makers to express their value judgements.

In the MAGIE model development process some important issues for the model improvement were identified. The most important of these issues was the interdependence that the inoperability of a specific bridge or tunnel can have in the level of importance of others structures. In other words, there was an interdependence of the actions. The resolution of such problem, although complex, can rely on the use of other types of *Impact Descriptors* that are stronger and more efficient in the assessment of the established goals (for example dynamic programming methods, simulation and traffic models in busy networks with multiple origins and destinations.).

To conclude, it is important to refer that the MAGIE model can be integrated in a Geographic Information System, allowing the global classification of the different bridges.

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