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CAPABILITIES OF THE BAYESIAN PROBABILISTIC NETWORKS APPROACH FOR EARTHQUAKE RISK MANAGEMENT

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SUMMARY

The present paper considers large-scale risk based decision making in regard to management of earthquake hazards. First an outline is given on existing methodologies on management of earthquake hazards in terms of capabilities and shortcomings. Thereafter a recently developed generic risk assessment framework is introduced which takes basis in a system representation through exposures, direct and indirect consequences as well as vulnerability and robustness. The framework is fully generic in the sense that the characteristics of the system are formulated in terms of risk indicators which may be specified in accordance with the available information concerning a given system. Furthermore, the framework is fully Bayesian such that probabilistic models and consequently also the risk assessments can be updated based on new information of relevance for the decision making. This in turns allows for considering the different decision situations, before, during and after an earthquake takes place, subject to the available information in the different situations. The basic properties of Bayesian Probabilistic Networks (BPN) are shortly introduced. Taking basis in previously developed BPN based risk assessment tools for vulnerability analysis of structures and soil, the presented framework is then illustrated through an example where a risk based decision analysis on possible retrofitting or rebuilding of building structures in a larger part of a city is performed for the two different situations - before and after an earthquake.

1. INTRODUCTION

A steady increase in damages and losses due to earthquakes can be observed around the world, mostly due to worldwide increased urbanisation in combination with insufficient resources and the resulting inadequate planning, design, execution and maintenance of building structures. Efficient management and consistent quantification of risks due to earthquakes is consequently becoming an issue of global societal concern. Support for decision makers at all levels, from supra national over national to local authorities and building owners, is required for three purposes; prevention, intervention and recovery, i.e. decision making in the situations before, during and after an earthquake takes place. All stated problems require engineering models and expertise from the disciplines of seismic hazard analysis, soil response assessment, structural response analysis, damage assessment and assessments of direct and indirect consequences. It is thus obvious that earthquake risk management necessitates an interdisciplinary treatment.

Significant research and development efforts have been allocated to the area of large scale earthquake risk management in the past. Within the framework of the International Decade for Natural Disaster Reduction

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(IDNDR) by the United Nations, a number of seismic risk assessment studies were carried out around the world. One of the major projects within this period is the RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters) project [GHI, 2004]. In this project, practical tools for a preliminary estimation of the possible damage scenarios and for the preparation of risk management plans for nine case study cities were developed. In Europe an initiative supported by the European Commission, RISK-UE, lead to the development of a methodology for assessing earthquake risk scenarios with special focus on the distinctive features of European cities, including existing buildings and monuments [Risk-UE, 2004]. In a major initiative in the U.S.A. the HAZUS [Whitman et al., 1997] earthquake loss estimation methodology was developed by the Federal Emergency Management Agency through the National Institute of Building Sciences.

The approach in the present paper utilizing Bayesian Probabilistic Networks (BPN's) for earthquake risk management on the basis of a generic and indicator based risk assessment framework has two major advantages as compared to the aforementioned previously developed methodologies. Firstly, an integral decision support system for consistently integrating all aspects affecting the damage on structures located within a region subjected to the same earthquake exposure is formed. The uncertainties which are influencing the functional chain of an earthquake from the source mechanism, the site effects, the structural response, the immediate direct consequences (damage) to the indirect consequences can be handled consistently in a Bayesian probabilistic framework. Secondly, with new information at hand a consistent updating of the risk assessments and thereby also the optimal decisions for risk management can be performed. This facilitates the extension of the approach to decision problems related to risk management during and after earthquakes.

Bayesian probabilistic networks, alternatively called belief networks or probabilistic causal networks, have become popular during the last two decades in the research areas of artificial intelligence, probability assessment and uncertainty modelling [Pearl, 1988]. The ideas and techniques have gained recognition also in other engineering disciplines and natural sciences, especially in problems involving high complexities and large uncertainties, see also Faber et al. [2002]. The description and assessment of natural hazards and the quantification of their related risks appears to be a problem for which BPN's can also be a helpful tool. In Bayraktarli et al. [2005] BPN's are applied to assess the earthquake risk for individual structures, in Straub [2005] to natural hazards risk assessment in general and in Grêt-Regamey and Straub [2006] BPN's are linked to a Geographic Information System (GIS) for natural hazards risk assessment.

2. EXISTING LOSS ESTIMATION METHODOLOGIES

The U.S. Federal Emergency Management Agency (FEMA) has developed the natural hazards risk assessment tool HAZUS for assessing physical, economical and human consequences of earthquakes, hurricanes and floods throughout the U.S. [FEMA, 2001]. HAZUS is a GIS-based tool to be used as a U.S.A. nation wide decision support tool for policy analysis, emergency response planning and disaster response preparedness in all levels – federal, regional and local. It enables analysis at three levels. At Level 1 national level data sets are used. At Level 2 local data may be substituted for the national data. At Level 3 besides the local data, specific analysis tools may be implemented by the user. Capabilities in HAZUS include *a hazard characterization tool* for earthquakes, floods and hurricanes, *damage analysis tool* for buildings and lifelines, *casualties and shelter estimation tool* and *economic analysis tool*. In the hazard characterization tool for scenario earthquakes with a specified magnitude and location, the probabilistic ground motion data is provided by the U.S.A. Geological Survey. HAZUS provides a general building stock database comprising 36 structural types (e.g. concrete frame with masonry infill) and 28 occupancy types (e.g. single-family dwelling). For each structural type capacity curves and fragility curves are provided. Capacity curves are used in combination with damping-modified response spectra to determine the peak structural response of the structure [ATC-40, 1996]. Fragility curves describe the exceedance probability of different damage states given the peak structural response. Damage probabilities are then calculated using the damage analysis tool. The casualty estimation tool estimates the number of injuries and deaths caused by structural damage. Using the economic analysis tool, building reconstruction costs, building content and inventory costs, business income and interruption costs, personal and rental income and disruption costs, and lifeline valuations can be estimated.

The RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters) initiative was launched in 1996 by the secretariat of the International Decade for Natural Disaster Reduction (IDNDR 1990-2000) of the United Nations. The main motivation was the inadequacy of the existing seismic risk assessment and management tools in application to developing countries. Nine case studies were carried out in two phases:

the evaluation phase and the planning phase. In the evaluation phase seismic risk assessment for a city was done by collecting existing data and estimating the potential damage due to a hypothetical earthquake. The potential damage was estimated theoretically and heuristically. In the theoretical estimation, seismic intensity distributions for the hypothetical event are combined with the building stock inventory and infrastructure using vulnerability functions. In the heuristic estimation, opinions from the local experts were collected through a series of interviews allowing adopting the special characteristics of the city system to be included in the damage estimation. In the planning phase the results of the evaluation phase were used in developing an action plan that would reduce the earthquake risk of the city. Using these case studies practical tools for earthquake damage estimation were developed providing a basis for similar efforts as a first step of earthquake risk management for other cities in developing countries [GHI, 2004].

The European Commission supported initiative RISK-UE developed a methodology for creating earthquake risk scenarios with special focus on the distinctive features of European cities. The aim was to produce a standard manual for assessing earthquake risk in urban areas, for use by all European countries. The initiative comprises two parts, a methodology enabling the assessment of seismic risk of European cities and an application of this methodology to seven EU and Eastern European cities. The methodology comprises a state-of-the-art seismic hazard assessment, a systematic inventory typology of the structures at risk with emphasis on distinctive features of European cities. Distinctive European urban features particularly concern complex building aggregates in old city centres and monuments and historical buildings. The classification of European buildings resulted in a European Building Typology Matrix (BTM), where 23 building types were identified leading to a total of 65 typologies. The vulnerability of the building typologies helping to identify the weak points of the infrastructure systems are estimated either by assigning a score or vulnerability index or by the capacity spectrum method [ATC-40, 1996]. The economic loss scenarios are based on the reposition cost of the buildings, the expected number of casualties and injuries has been obtained by the model proposed by Coburn and Spence [2002]. The established earthquake scenarios, structured within a GIS, could then be put forward to town councils as a basis for discussion and drawing up plans of action for systematically reducing earthquake risk [Risk-UE, 2004].

3. BAYESIAN PROBABILISTIC NETWORKS FOR EARTHQUAKE RISK MANAGEMENT

A risk assessment framework distinguishing three levels, namely exposure, vulnerability and robustness, is considered. The exposure, *EX*, is considered as an indicator of the seismic hazard potential for the city or region of consideration. It is an inherently uncertain phenomenon with probabilistic characteristics usually provided in terms of earthquake ground motion intensities and corresponding return periods. Vulnerability, assessed through the probability $P(D|EX)$, is considered as an indicator of immediate consequences, C_D of damage D to the structural or non-structural elements associated with a given earthquake. Vulnerability is associated with significant uncertainty and is appropriately described by a probability distribution of different damage states of structures conditional on the exposure event, e.g. the spectral displacement. The modelling of uncertainty associated with the assessment of exposure and vulnerability may be based on well established frameworks such as the Joint Committee on Structural Safety Probabilistic Model Code, [JCSS, 2001]. Robustness, assessed through the complement of the probability $P(ID|D,EX)$, is an indicator of the indirect consequences, C_{ID} of the indirect damages ID due to the damages, D, on the structural or non-structural elements of the buildings. Robustness is associated with the conditional probability of losses of various degrees, conditional on the exposure and a given damage state. The uncertainties involved in the assessment of the robustness contain significant epistemic uncertainty. One of the reasons for the significant subjective element of uncertainty in consequence modelling is the uncertainty in regard to appropriateness and completeness of the applied consequence assessment models. However, in correspondence with the risk assessment framework outlined in the above and consistent with Faber and Maes [2003] it is proposed to perform the risk assessment on the basis of the following expression for the risk or the equivalent expected direct and indirect consequences:

$$\begin{aligned} R &= E\left[C_D + C_{ID}\right] = \\ &\iint C_D\, p\left(D|EX\right) p\left(EX\right) dD\, dEX + \iiint C_{ID}\, p\left(ID|D,EX\right) p\left(D|EX\right) p\left(EX\right) dID\, dD\, dEX \end{aligned} \tag{1}$$

For assessing the risk, BPN's are applied to establish a generic model of the causal relations between the seismic hazard, the vulnerability of the building stock and the possible consequences. This model also involves a number of observable characteristics which comprise so-called indicators.

3.1 Definition of a Bayesian Probabilistic Network

BPN's constitute a flexible, intuitive and strong model framework for Bayesian probabilistic analysis [Jensen, 2001]. BPN's may replace both fault and event trees and can be used at any stage of a risk analysis. Due to their mind mapping characteristic, they comprise a significant support in the early phases of a risk analysis, where the main task is to identify the potential hazard scenarios and the interrelation of events leading to adverse events. BPN's also provide strong tools for risk based decision analysis, including prior analysis, posterior analysis and pre-posteriori analysis. Furthermore, they may be applied for the purpose of diagnosing systems, i.e. identifying the event scenarios, which with the largest likelihood lead to specific adverse events of interest.

N is a Bayesian network triplet (V, A, P), where:

- V is a set of variables $v_i, i = 1,2,3...$.
- A is a set of links showing causal interrelations between the variables. The links A and the variable set V constitute a directed acyclic graph.
- $P = \{P(v \mid \pi_v) : v \in V\}$, where π_v is the set of parents of v. In words P is the set the conditional probabilities of the all variables given their parents.

It is common to visualize the variables in a BPN as nodes. Two additional elements, decision nodes and utility nodes, may be added to a BPN, enabling the BPN to solve decision problems. Such BPN's are also known as influence diagrams. A decision node visualized by a rectangle shows the alternative actions to be chosen by the decision maker and utility nodes visualized by diamonds show the consequences of the chosen action. A BPN may be formulated by the following steps, see also Figure 1:

- Variables necessary and sufficient to model the problem framework of interest are identified.
- Causal interrelations existing between the nodes are formulated, graphically shown by arrows.
- A number of discrete mutually exclusive states are assigned to each variable.
- Probability tables are assigned for the states of each of the variables.

More formally, the BPN maps the joint probability distribution, $P_N(V)$, of a considered system:

$$P_N(V) = \prod_{v \in V} P(v \mid \pi_v) \tag{2}$$

As an example, for the principle BPN in Figure 1 the joint probability is given by:

$$P_N(A,B,C,D,U) = P(A)P(B)P(C \mid A,B,D) \tag{3}$$

The marginal probability of any variable, say variable *C* in Figure 1, is assessed by marginalizing all variables different from variable *C* out of the joint probability:

$$P_N(C) = \sum_{V/C} P_N(V) \tag{4}$$

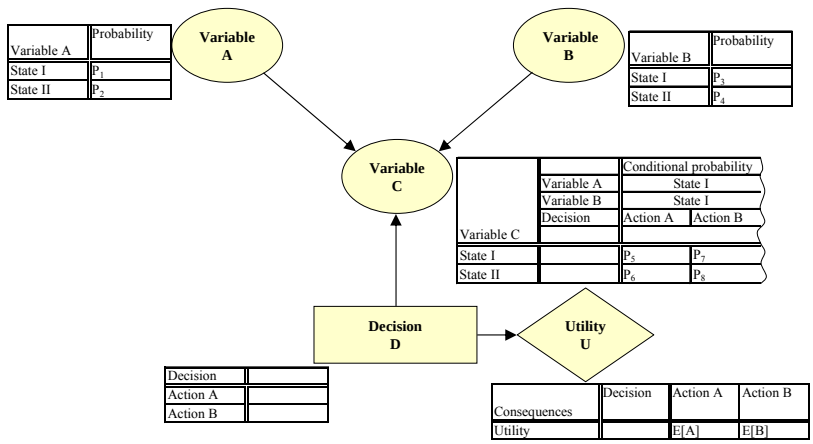

Figure 1. A principle BPN with states and probability tables.

There may be evidence that some of the variables have specific values. For example, the variable *B* in the BPN in Figure 1 may be observed to be in State I. Then the posterior probability of any variable in the BPN, for example of variable *C* is assessed as:

$$P_N(C \mid B = \text{State I}) = \frac{P_N(C, B = \text{State I})}{P_N(B = \text{State I})} \tag{5}$$

Efficient so-called inference engines are available for the numerical evaluation of Equations (3)-(5) [Jensen, 2001].

3.2 Approach, capabilities and added value of using BPN's for earthquake risk management

In a first step the decision problems are identified and formulated such that they may be represented and assessed individually in prior decision analysis [see e.g. Benjamin and Cornell, 1970] for the purpose of identifying activities for efficient risk reduction. Secondly, risk management decision alternatives are identified including in principle all known measures of risk mitigation and risk treatment such as options for strengthening, rebuilding and redefinition of use of structures. Furthermore, the decision problems are also assessed by means of pre-posterior decision analysis [Benjamin and Cornell, 1970] for the purpose of identifying how additional information may efficiently reduce the risks. A consistent basis for the representation of the uncertainties influencing the decision problems is then developed and specified in accordance with Faber [2003], i.e. uncertainties associated with the exposure, vulnerability of the structures and soil as well as the uncertainties associated with robustness.

BPN's are envisaged to be applied for the quantitative risk assessment such that the risk analysis may be formulated in a generic format by means of key indicators. For each decision situation a BPN is constructed mapping the functional chain of the earthquake by considering indicators which may be updated with incoming information during and after an earthquake. The uncertainties associated with the indicators are included in the BPN. As for the other mentioned loss estimation tools, existing state-of-the-art procedures for seismic hazard analysis, vulnerability assessment, damage assessment and consequences assessment can be used. The probability tables are generated using generic models for the soil behaviour and performance assessment of the structures. This enables the BPN's to be applied to any city or region with its specific characteristics. The specific characteristics of the cities in terms of earthquake hazards, soil characteristics and building categories are accounted for through the respective nodes of the BPN. The input and output used and generated by the BPN's are organized in a Geographical Information System (GIS). Using the BPN, diagnostic analysis can be performed to identify the main risk contributing damage scenarios. The results of this assessment may be used at a later stage for the purpose of identifying how risk reduction and mitigation may be implemented most efficiently.

Additional information after an earthquake can be supplied by e.g. photogrammetric techniques in the form of residual displacements of the top of the structures or by detection of heavily damaged or collapsed buildings. Since the performance assessment of the structures is performed taking into account residual displacements, both types of information are used to update the model. When considering large scale studies, aerial photogrammetry may also be used for inventory purposes, i.e. the identification of the building stock, the height and consequently the number of stories of the building and the distance and orientation of the buildings to known seismic sources.

Using BPN for earthquake risk management provides a generic model basis which allows for a consistent modelling of the relevant uncertainties in accordance with available information. Furthermore, BPN's accommodate for enhanced communication between experts, decision makers and stakeholders in an interdisciplinary context. Unlike the aforementioned previously developed frameworks the loss estimation tool is integrated in the decision support framework so that communication to non earthquake engineering experts such as emergency planners, urban planners and decision makers is greatly improved. BPN's offer a high level of analysis sophistication and enable decision makers to perform various `if - then' scenarios to study the sensitivity of the results, to develop a better understanding of the outcomes and to gain insight into the consequences of the decisions.

4. EXAMPLE APPLICATION

The example application aims to illustrate the application of the BPN based framework for risk based management of earthquake risk for the purpose of identifying adequate risk reducing measures for a test area in the city centre of Adapazari/Turkey. Furthermore, it is also shown how Geographical Information Systems (GIS) technology can be applied in managing, evaluating and graphically representing seismic risk data. The city centre of Adapazari suffered extensive losses during the 17th August, 1999 Kocaeli M_w7.4 earthquake. Many buildings in the city suffered damages also due to liquefaction induced ground settlements during the earthquake. In the example three decision alternatives, namely, retrofitting the structures, improving the soil or no action are considered.

4.1 Test area

A test area in the city centre of Adapazari is chosen to illustrate the application of the generic indicator based approach using BPN (Figure 2). The test area includes the most affected region of the city during the Kocaeli Mw7.4 earthquake as well as areas with liquefaction during the same event [DRM, 2004]. All available data are organized in a Geographical Information Systems (GIS) platform. The GIS platform is chosen since it is necessary to collect, analyse and appropriately match a rather large quantity of partly spatial data. GIS allows easy display of input and output providing functionality for communication of results to third parties as emergency planners and decision makers.

Figure 2: Test area for the example application.

The building stock in the test area comprises 2194 1-story, 2715 2-story, 1143 3-story, 655 4-story, 431 5-story, 47 6-story and 1 7-story building totaling 7186 buildings. The lateral load resisting system of the buildings is assumed to be reinforced concrete moment resisting frames (RCMRF). In the GIS database the number of stories, story area and critical soil layer in regard to liquefaction potential is stored.

4.2 Application of the Bayesian Network approach

In the example three decision alternatives, namely strengthening the reinforced concrete moment resisting frames by structural walls, preventing liquefaction of the soils underneath the foundations by stone columns or no action are considered. The BPN for the decision problem is given in Figure 3. The BPN is applied for all 7186 buildings in the test area with the specific data of each building concerning the structure class it belongs, the story area and the critical soil layer in the location of the building, giving the optimal action for the building. After an earthquake has happened the BPN model is updated with hypothetical information on the damage state or measured residual displacements on the top of the buildings by photogrammetric techniques and the optimal actions are recalculated. In the following the nodes of Figure 3 are discussed. In Figure 4 the results of the BPN analysis for the test area are given, indicating for the situations before and after an earthquake the optimal actions to be taken for each building in the test area.

4.2.1 Indicators related to exposure

The seismic activity related to the source zone is considered as a point source. The probabilities for the occurrence of earthquakes with specific magnitudes are considered in the 'EQ magnitude' node. The annual probabilities for each Mw (Mw=5.5, 6.5, 7.0, 7.5) are calculated using the Gutenberg-Richter magnitude recurrence relationship [Gutenberg and Richter, 1944]. Recurrence rate parameters corresponding to the North Anatolian Fault source zone are taken from Erdik et al. [1985]. The probability distribution of the distances of

the test area to the seismic sources is presented by the 'EQ distance' node. The seismic sources are assumed to be R=10 km, 20 km, 40 km and 80 km from the test area.

For the earthquake demand modeling a set of acceleration time histories is generated. The attenuation relationship proposed by Boore et al. [1997] for estimating the pseudo-acceleration response spectra for the random horizontal component at 5% damping, is used for the synthesis of the ground motion time histories. 16 pairs of moment magnitudes (5.5, 6.5, 7.0, 7.5), epicenter distances (10, 20, 40, 80 km) and site class (sand) are selected and using a version of SIMQKE [Gasparini and Vanmarcke, 1976] modified by Lestuzzi [2000] 20 samples of accelerogram time histories for each pair of these are generated, resulting in 320 simulations. For all combinations of (Mw, R) and depending on the fundamental periods of the structures, the spectral displacement values are estimated by the attenuation relationship proposed by Boore et al. [1997]. The seismic demand node consists of these spectral displacement values. 'PGA (Peak Ground Acceleration)' is assumed to be independent of 'Spectral displacement' but dependent on the 'EQ magnitude', 'EQ distance' and 'Soil type'. The states of 'PGA' are taken from the simulated acceleration time histories.

4.2.2 Indicators related to vulnerability

One of the most critical subcomponents of earthquake risk management is the assessment of seismic performance of the structural stock. Assessment of the performance of an individual structure is an intricate task by itself. Therefore, in order to investigate large building stocks it is inevitable to simplify the process by grouping the structures which are expected to have a similar seismic performance. In this study the available reinforced concrete moment resisting frame (MRF) building stock is grouped into seven "structural classes" based on their number of stories. In addition to these, the possible retrofitted states for each of these structural classes are represented by another group of seven structural classes. Addition of two reinforced concrete structural walls per main direction of the building was selected as the retrofitting action of interest for the structures. Introduction of structural walls, results in a significant increase in the lateral stiffness and base-shear capacity of the building. A total of 14 single-degree-of-freedom (SDOF) systems with modified Takeda hysteresis are defined as substitute-systems for representing the dynamic characteristics of each structural class. The dynamic properties of the substitute SDOF systems are assigned according to the relationships proposed by Priestley [1998] and the Turkish Seismic Code [1998]. The yield displacements and base-shear capacities of the retrofitted buildings are estimated according to the procedure by Dazio [2000]. The response of substitute-SDOF systems to the whole set of acceleration time histories, are simulated.

It is conventional to assume that, the maximum and residual displacements attained by the substitute-SDOF systems can be used as an estimate of those to be attained by the real structures themselves. In general terms, for the case of maximum displacements of buildings excited dynamically predominantly in their first mode this assumption has been verified. However, for the case of residual displacements it should be noted that the adopted modeling approach has a significant impact on the computed results [Yazgan & Dazio, 2006]. For the clarity of the example application it will be assumed that the residual displacements computed for a substitute-SDOF system can be used as an estimate for the residual displacements of the buildings in the corresponding structural class. Maximum displacements are known to be well correlated with structural damages. Furthermore, residual displacements are critical for the post-earthquake usability/reparability of a structure. These two structural response parameters together can provide a good picture of the seismic performance of a structure. The performance level definitions provided in the Vision 2000 [SEAOC, 1995] were adopted to relate the structural response parameters to the damage states. It should be noted that the modular structure of the framework provides the capability of adopting more advanced definitions of structural performance.

The node 'Soil type' constitutes the states rock, gravel, sand, silt and clay. 'Soil profile' constitutes the different layers of the considered soil profile. The 'Modified Chinese Criteria' [Andrews and Martin, 2000] is implemented as a logical connection in 'Liquefaction susceptibility'. Using this criteria soil having a liquid limit LL≥32 and clay content CC≥10% are regarded as not susceptible for liquefaction. The node 'Liquefaction triggering' comprises the conditional probabilities for liquefaction triggering computed based on empirical models which relate the standard penetration test (SPT) blow count and observed liquefaction from past earthquakes [Youd et al., 2001]. 'Soil response' has two mutually exclusive states 'ground amplification' and 'liquefaction'. As retrofitting measure for the subsoil substituting stone columns on each side of the building down to two meters below the foundation level is considered [Has Inşaat, 2006]. It is assumed that the liquefaction potential of the critical soil layer is fully eliminated by this measure.

4.2.3 Indicators related to robustness

In the decision problem identified for the present example costs associated with retrofitting, rebuilding and loss of life are considered. For Turkey, the average unit retrofitting cost for installation stone columns is estimated as 40 EURO/m^3 inserted gravel, the average unit rebuilding cost as 120 EURO/m^2 floor area and the average unit retrofitting cost for adding a structural wall as 16 EURO/m^2 floor area [Has Inşaat, 2006]. Loss of lives of individuals is quantified by the Societal Life Saving Cost (SLSC) [Rackwitz, 2003], which is derived based on the Life Quality Index [Nathwani et al., 1997]. For Turkey, based on data for year 2004, the SLSC is estimated as 105'000 EURO per fatality. All costs due to earthquake induced losses taking place in the future are discounted using a discount rate of 2% [see e.g. Rackwitz et al., 2006].

4.2.4 Decision making

For the identified decision situation possible activities are given in the 'Actions' node. In the 'Actions' node 'No action', 'Adding structural walls and 'Installation of stone columns' are considered as decision alternatives. The consequences of these actions are implemented in terms of costs, conditional on the damage, story area and the number of fatalities. Direct consequences, i.e. the 'Damage' node as well as indirect consequences, i.e. 'Number of fatalities' node, are considered when implementing the table for the 'Costs' node. Damage can influence the cost directly, i.e. for the damage state "near collapse" and "collapse" rebuilding costs are considered, or indirectly over the number of fatalities. Having quantified the probability tables and consequences the example BPN is used for risk assessment and decision analysis. For the BPN analysis the software package Hugin [Hugin, 2006] is used. The optimal decision is based on a comparison of the expected total consequences of the alternative actions given the reference period. With information for each building in the test area on story area, number of stories and critical soil layer underneath the building an optimal action is calculated using the BPN. Using the 'Planimetry measure' node, the information from photogrammetric measurements after an earthquake is used for each building to update the optimal decision. The buildings identified as 'nearly collapsed' or 'collapsed' by the photogrammetric measurements are excluded from the BPN analysis and identified as 'to be rebuild'. The results are given in Figure 4.

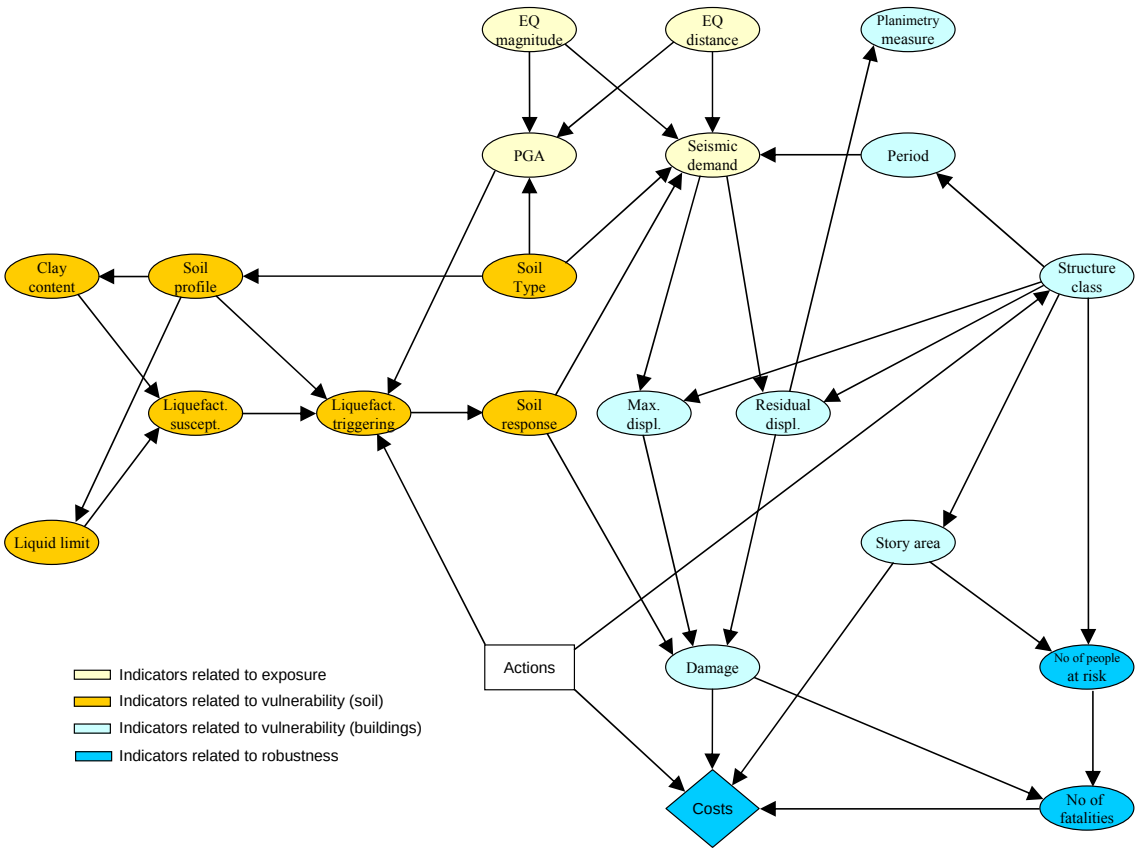

Figure 3: BPN for the decision analysis.

Figure 4: Optimal decision for each building (left before, right after the earthquake).

5. CONCLUSIONS

Large scale earthquake hazards risk management is considered utilizing a newly developed indicator based risk assessment framework together with Bayesian Probabilistic Networks (BPN) and Geographical Information Systems (GIS) models. The proposed framework uses similar models in regard to the seismic hazard analysis, vulnerability assessment, damage assessment and consequence estimation as existing methodologies like HAZUS, RADIUS or RISK-UE. The advantage of the framework proposed here is mainly related to four important aspects: The proposed framework is fully generic in the sense that it can be easily adapted for use in a given region by means of risk indicators representing the main characteristics of the system subject to risk assessment. The probabilistic modelling of the uncertainties which have relevance for the risk assessments is fully Bayesian, which in turn facilitates for updating of the risk assessment model as well as optimal decision when new information about the considered system becomes available. The proposed risk assessment framework sets focus on a differentiation between direct and indirect consequences whereby characteristics of the considered system in regard to vulnerability and robustness can be assessed. Finally, the BPN's besides of forming a very efficient tool for risk assessment also have the benefit of facilitating straight forward communication of the applied risk assessment models between experts, decision makers as well as stakeholders.

The application of BPN for earthquake risk management is illustrated on a decision problem concerning the optimal actions of retrofitting structures or improving the soil in a test area in Adapazari, Turkey. The building stock which is comprised of 7186 buildings is classified into seven structure classes depending on their number of stories. Since liquefaction phenomena were observed after the past earthquakes in Adapazari, the critical soil layers in regard to liquefaction are identified for the different regions in the test area. The information of relevance for the risk assessments of the individual buildings is organized using GIS databases. Using BPN's which have been linked with the GIS databases including models of soil liquefaction failure as well as models of building damages the optimal action for each building are identified. For the purpose of illustration, the risk assessment model is thereafter updated corresponding to a situation where an earthquake has taken place. The optimal action is then reassessed with hypothetical information on the damage state or measured residual displacements of the top of the buildings by photogrammetric techniques.

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