Prediction Models of Infrastructure Resilience as a Decision Support System Based on Bayesian Network

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Abstract. The impact of climate change is the implication of global warming that affects people around the world, including Indonesia, which is causing more the intensity and type of natural disaster that causes a decrease or malfunction of a city. To reduce the impact of climate change is needed for the application of the concept of resilience. Resilience is the ability to withstand disturbances caused by external factors and the ability to recover if damage occurs. One of the natural disasters is an earthquake is a natural disaster that often occurs in Indonesia and generally causes significant damage to the physical condition of buildings and infrastructure. This study aims to create a prediction model to measure the impact of a disaster as a decision support system such as a mitigation strategy and responses to identify measures that can improve performance infrastructure to meet resilience goals. One of probabilistic methods is the Bayesian Network method. It is a graphical model probabilistic that represents a set of variables and freedom probabilistic using conditional-probability-table. This research expects as a proposed method of assessing resilience infrastructure to cities in Indonesia when natural disasters occur, especially earthquakes.

1. Introduction
Climate change is causing more intensity and types of natural disasters, such as floods, earthquakes, drought, tornadoes, uncertain seasons, decreased agricultural productivity, and disease outbreaks. One of the natural disasters is an earthquake is a natural disaster that often occurs in Indonesia and generally causes significant damage to the physical condition of buildings and infrastructure. During 11 years (2009-2019), Indonesia recorded as having 71,628 earthquake events, with an average tectonic earthquake activity of 6,512 events per year, 543 events per month, and 18 earthquake events per day [1].

Reducing the impact of disasters that cause damage to buildings and infrastructure, it is necessary to apply the concept of resilience so that cities start moving in the context of climate change. Resilience is defined differently depending on the field of study [2]. In engineering, Resilience is the ability to withstand disturbances caused by external factors and the ability to recover if damage occurs [3]. However, research on quantitative assessment methods on resilience is still in its early stages of development, there is no general method that can be generally applied. One method is to use a standard resilience indicator-based methodology, which is an effective method for measuring the level of resilience because it allows modeling of complex systems easily and effectively [3]. On the other hand, several authors propose an indicator-based methodology for evaluating resilience in engineering studies; some are deterministic and others are probabilistic [4]. The main challenges are the uncertainty in the resilience model input. The deterministic method cannot be used to model the interdependence and distribution of weighting factors between variables [4]. Therefore, probabilistic methods are more
common to use than deterministic methods. Probabilistic models can model uncertainty and interdependency and are more appropriate for representing reality. Previous research, not all probabilistic approaches are suitable for modeling systems engineering behavior, especially in cases where past data are not available. One way to model system behavior probabilistically is the Bayesian Network (BN) [4]. The Bayesian Network (BN) method is necessary to use for knowledge representation and reasoning under uncertainty, especially in the context of partial data information [4]. Previous research is based on indicators and no qualitative and quantitative measurement method can be generally applied to other cities in Indonesia. Assessment methods to measure how resilience a city has not been developed in Indonesia at this time. Therefore, this study aims to create predictive models to assess the impact of decision support system options such as mitigation strategies and response to identify measures that can improve infrastructure performance to meet resilience objectives. This study is a decision support system in measuring infrastructure resilience assessment based on infrastructure hazards to achieve resilience goals after a disaster with a probabilistic infrastructure resilience model using the Bayesian Network.

2. Literature Review

2.1. Bayesian Network

Bayesian Network initiated by Mr. Rev Thomas Bayes, following the rules of a mathematical formula in the form of conditional probability theory. The most basic Bayes equations are:

\[ P(b | a) = P(a | b) \times P(b) \times P(a) \] (1)

P (a) is probability a, and P (b) is probability b, and P (a/b) is probability a if it is known that event b has occurred. Bayesian Network is a graphical probabilistic model that represents a set of variables and their probabilistic freedom. In Bayesian Network modeling using a Directed Acyclic Graph (DAG), where each node represents one variable and the arc (edge) represents the dependency conditions between variables. This dependence is measured by the conditional probability for each node with its parent node [5].

The BN method is effective when various types of variables and knowledge from various sources need to be integrated into one framework. In addition, BN provides a probabilistic relationship between variables, which allows modeling of interdependencies between variables. In the literature, there are a number of research contributions that use BN in resilience analysis that propose a probabilistic methodology based on the BN approach to model the interdependence of critical infrastructure systems [6]. Their research aims to understand the effects of interdependence on the fragility of the system as a whole. Other research develops universal resilience metrics for infrastructure systems.

2.2. Variable Synthesis

Variable synthesis is the result of a summary of the variables towards research related to resilience goals. Based on the results of a literature study revealed by several researchers. Although the objects and objectives of the research that are the source of the literature are different but still in the context of repair time and performance, the most influential thing is the target of the recovery process so that it can determine the value of resilience when a disaster occurs.

Previous research on infrastructure resilience used several methods with the summaries shown in table 1 below.
Table 1. Related research of infrastructure resilience

| Authors | Method                  | Result                                                                                                                                                                                                                                                                                                                                 |
|---------|-------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [7]     | Loss Triangle approach  | The loss triangle approach method, which quantifies resilience based on the loss of performance of the integrated system during the time it takes for the system to recover after a disturbance. Performance measures used in this context include those based on the operability of network connectivity assets, network capacity, satisfactory demand, and value of services provided. The comparison between adaptation plans and resilience plans has a low value on the uncertainty principle, but resilience plans have significantly lower value than adaptation plans. This research is only used if there is a specific plan for a strategy that is flexible, robust, and satisfying (i.e., a strategy that can be modified over time or will achieve benefits in the future) as well as a strategy for building a flexible or robust system (i.e., infrastructure or systems that will be able to transform and recover from extreme disasters). |
| [8]     | Plan evaluation/Survey  | A Bayesian Network based probabilistic model, developed to assess interdependent network resilience in a full-service deep-water port case study. The comparison between adaptation plans and resilience plans has a low value on the uncertainty principle, but resilience plans have significantly lower value than adaptation plans. This research is only used if there is a specific plan for a strategy that is flexible, robust, and satisfying (i.e., a strategy that can be modified over time or will achieve benefits in the future) as well as a strategy for building a flexible or robust system (i.e., infrastructure or systems that will be able to transform and recover from extreme disasters). |
| [9]     | A Bayesian Network based approach | A Bayesian Network based probabilistic model, developed to assess interdependent network resilience in a full-service deep-water port case study. The comparison between adaptation plans and resilience plans has a low value on the uncertainty principle, but resilience plans have significantly lower value than adaptation plans. This research is only used if there is a specific plan for a strategy that is flexible, robust, and satisfying (i.e., a strategy that can be modified over time or will achieve benefits in the future) as well as a strategy for building a flexible or robust system (i.e., infrastructure or systems that will be able to transform and recover from extreme disasters). |
| [10]    | Bayesian Network and Monte Carlo Simulation | Bayesian Network and Monte Carlo Simulation framework as a decision support system to quantify and improve infrastructure resilience which considers several hazards and interdependencies between infrastructure. The framework also includes decision support options and community expectations. Resilience is codified using the Bayesian Network which is applied to Seaside, Oregon, for earthquake and tsunami hazard conditions. |
| [4]     | Bayesian dan Dynamic Bayesian Network | Static framework and dynamic framework for assess resilience in Bayesian Network-based engineering systems. Using model indicators on the transportation network with two case studies as a demonstration of the implementation of the framework. |

The development of variables for quantitative prediction methods also needs to be developed by synthesizing several research variables in resilience.

3. Research Methodology
Research Methodology first stage is compiling the background and research objectives. The second stage is compiling the gap analysis. The third stage is reviewing relevant previous research results and identifying variables that affect resilience infrastructure, and pre-surveying to make proposals for predictive models that are suitable for measuring resilience infrastructure based on conditions in Indonesia. The fourth stage is the identification of variables derived from the literature study, pre-survey, and expert judgment. The fifth stage of modeling, determining the variables that affect the resilience infrastructure through the identification of variables, variable relationships validated by the expert and conditional probability table (CPT). The sixth stage, the stage of validating the form model, validating the results of the model diagram with the Bayesian network. Furthermore, discussions and discussions are held to reach conclusions and suggestions.

4. Model Simulation of Infrastructure Resilience

4.1. Schematic Model
In the Bayesian Network concept, figure 1 below illustrates natural disasters (D) with case studies of earthquakes affecting infrastructure conditions. However, there are other factors besides earthquakes...
that affect the condition of the infrastructure building, the existing condition of the infrastructure building itself, such as maintenance of the building or infrastructure and also the location of the point where the earthquake occurred on bridge buildings and water structures, as well as the extent of damage to road infrastructure, these other factors are summarized in the category observation (O). In the observation stage, an assessment of the condition of the building before an earthquake occurs, the latest data on reporting of maintenance or maintenance can be used, if the data is not available, expert opinion will be input for the assessment of the observation stage. Furthermore, the physical form of infrastructure and buildings after the disaster is categorized in the form of infrastructure (If). Factors that support the resilience variable such as the final result of the physical condition of the building after a post-disaster assessment and related regulations that support resilience are categorized in the indicator category (Id). In the next stage, the existing conditions and factors are summarized in resilience variables (V) in the form of vulnerability, robustness, and recoverability. These three variables determine the condition of resilience (R) in a city.

Figure 1. Schematic of resilience infrastructure

4.2. Model Simulation
The model developed is based on the types of disasters that occur and it is hoped that for all types of disasters there is a framework to determine the resilience value of infrastructure all over Indonesia. This simulation takes a case study of the earthquake disaster on its effect on buildings, roads and bridges as one of the priorities in the post-disaster recovery process. The schematic above is developed for the Bayesian model as in Figure 2 below.
4.2.1 Simulation 1
Earthquake conditions did not occur, existing building conditions were by Indonesian National Standard, in good condition, maintenance was carried out, but there were no strategies and policies related to disaster risk reduction that supported resilience. The results of the simulation can be seen in Figure 3 below with the output resilience high 12%, medium 45%, and low 42%, so it can be concluded that the results of the medium-low value in this simulation condition.

4.2.2 Simulation 2
Earthquake conditions that occur are high, existing conditions of buildings according to SNI, slightly damaged conditions, near to the disaster location, no maintenance is done, and there are no strategies and policies related to disaster risk reduction that support resilience. The results of the simulation can
be seen in Figure 4 below with the output resilience high 9%, medium 29%, and low 62%, so it can be concluded that the results of the low value in this simulation condition.

![Figure 4. Model Simulation 2 of Resilience Infrastructure](image)

5. Result and Analysis
All the results drawn from this research indicate that the Bayesian Network model can effectively address mutual interdependency of disaster risk analysis and provide recommendations to mitigate risk. Although Bayesian Network has been applied in different research, two significant gaps are identified and need to be addressed. These gaps are the need for a Bayesian framework to design an interdependent infrastructure system that takes into consideration the complex interactions that exist among different entities of the entire network. The lack of research assessing the resilience of infrastructure concerning the concept of vulnerability, robustness, and recoverability.

From the simulation below, the sensitivity analysis for scenario 1 sensitivity analysis can be seen in figure 5 below. Conditions that greatly affect the results of the level of resilience from figures 6 represent the condition of the infrastructure building after being observed in good conditions so that it produces good performance, but because there are no strategies and policies related to disaster risk reduction, the variable resilience condition shows low vulnerability 87%, medium robustness 57 %, and recoverability slowly 90%. So that the results of the resilience level are at medium-low with a result of 45% -42%.
Figure 5. Result of model simulation 1 of resilience infrastructure

From the simulation 2 above, the sensitivity analysis for the scenario 2 sensitivity analysis can be seen in figure 6 below. The conditions that greatly affect the results of the resilience level from figures 6 is the condition of the infrastructure building after the observation was carried out with moderate damage and significant damage conditions resulting in a significant performance of 33% damage, but because there are no strategies and policies related to disaster risk reduction, the variable resilience condition shows vulnerability, low 87%, robustness low 58%, and recoverability slowly 90%. So that the results of the level of resilience are low with a result of 62%.

Figure 6. Result of model simulation 2 of resilience infrastructure

6. Conclusions
The Bayesian Network method approach can be used to assess the resilience infrastructure by considering different disruptive scenarios to assess the resilience of infrastructure. The simulation shows that each observation of buildings and infrastructure conditions pre-disaster contributes to determining
the performance. The model scenarios also provide clarity that the effect on the resilience condition is provided by, strategies and policies of disaster risk reduction. The Bayesian updating approach can also be used as a guide for the maintenance and operation strategy of the buildings and infrastructure. To prevent the sudden collapse of the buildings and infrastructure. Finally, the proposed model can also be used as an early warning system to prevent structural failure of buildings and infrastructure, even though the model accuracy still needs to be improved.

7. References

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