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Risk modelling with Bayesian Networks - case study: construction of tunnel under the Dead Vistula River in Gdansk

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Abstract

The process of decision-making in public procurement of construction projects during the preparation and implementation phases ought to be supported by risk identification, assessment, and management. In risk assessment one has to take into account factors that lead to risk events (background info), as well as the information about the risk symptoms (monitoring info). Typically once the risks have been assessed a decision-maker has to consider risk-management activities that minimise the risk events (mitigating factors). Finally, the decision-maker has to select best response decision(s), i.e., one that would either maximise the benefits or minimise the losses. This selection is best performed in the framework of the utility theory. Thus, a good diagnostic-decision support model (D-DSM) has to integrate the following elements: background info, risk events, monitoring info, mitigation activities, response decisions, and associated with risk events and decisions utilities. Our purpose is to demonstrate how Bayesian Belief Networks (BBNs) can be used as D-DSM to assess and manage risks, and finally select best response decisions, during the implementation phase of a large construction project.
The authors use the example of a road tunnel under the Dead Vistula River in Gdansk (Poland). The D-DSM combines expert knowledge about the relationships among model components with the monitoring information. The model is able to use evidence from various sources in a mathematically rigorous manner. We demonstrate how the model may be used to estimate: the value of monitoring information (from the utility and diagnosis uncertainty perspectives) and the benefits of mitigation activities.

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Keywords: Bayesian network; construction management; monitoring; risk assessment; value of information.

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1. Introduction

To large extent, the success of a construction project depends on effective risk management, which in turn is concerned with correct evaluation of the probability of adverse events, particularly when new observations/evidence becomes available. These issues are not typically considered in the planning phase, which results in a lack of consistency between the design assumptions and the construction phase [1].

The purpose of the article is to demonstrate the possibility of using the Bayesian Belief Networks (BBNs) in the diagnostic-decision support model (D-DSM), In particular we are concerned with risk assessment and management for large construction projects. As an example we use a unique high-cost project with complex technology, namely the construction of a road tunnel under the Dead Vistula River in Gdansk. The application of the BBNs to this case helps us in assessing and managing the risks in the environment of uncertainty. This is achieved by a combination of monitoring data and expert knowledge [2,3]. The latter is used to determine the connections among the system's elements, whose strength is expressed by relevant conditional probabilities. Project planning that takes into account the risks of work disruption is a very important component of the investment process, as it reduces the probability of delaying each step of the construction, and thus also contributes to the reduction of unexpected extra costs, especially those related to the penalties for delays [4].

1.1. Data for BBN construction

For the analysis of risk and the estimation of the its value during the construction of the tunnel under the Dead Vistula River in Gdansk we build a probabilistic model based on the Bayesian Belief Network methodology [5,6]. For computer simulations we used the Netica software (Norsys - Netica Application - Norsys Software Corp) [7]. First, the analysis of project documentation was conducted and its results were combined with the information provided by the customer - Gdańskie Inwestycje Komunalna Sp. z o.o., To determine the network parameters (conditional probability tables and utilities) we used the expert brainstorming approach. After the initial network was created we verified its behaviour by performing numerous simulations and comparing the results to the experts' expectations. This seems to be a common approach for developing AI tools.

The risk model development for the tunnel under the Dead Vistula River in Gdansk began from the division of risks into four basic groups covering: the general risks, the risks resulting from the contractor's activities, the technical risks, and the executive risks [8,9]. In this paper, special attention is given to the high degree of risk arising from the technology and the work performance, due to the long duration of the investment and its unique character. In this group we identified the risk of damage to Tunnel Boring Machine, the risk of collisions of the construction work with existing underground networks, as well as the risk of damage to the existing adjacent facilities. Experts recognised that the analysis of all potential sources (factors) of risk is not feasible, and, in addition, such high resolution may distort the actual picture of the most important issues. In this example, we analysed only the factors that are most important from the customer's point. These factors constitute a sample set chosen for the examined risk behaviour.

2. Description of the decision problem

The purpose of the decision model presented on Figure 1 is to answer the question: whether to continue tunnel drilling activities considering updated (based on monitoring evidence) probabilities of selected risk events.

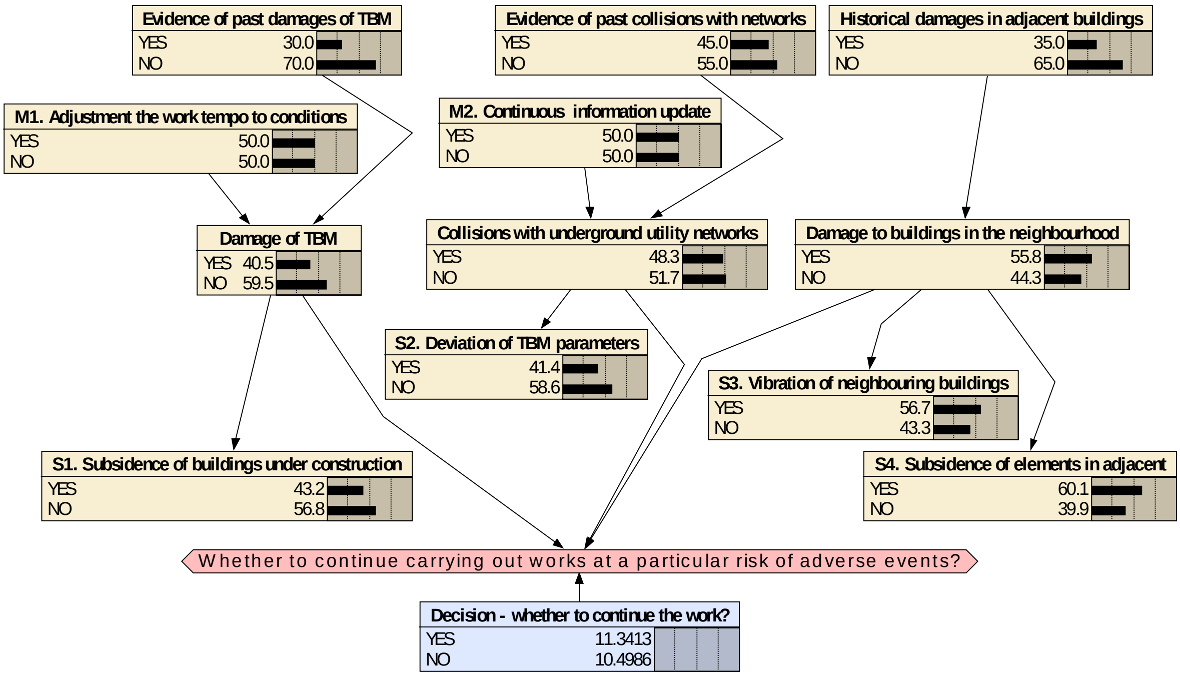

Fig. 1. Bayesian network diagram for technical risk made in the Netica, source: own study, http://www.norsys.com/download.html

The decision depends on three main decision variables, i.e., damage of Tunnel Boring Machine, collisions with underground utility networks, and damage to buildings in the neighbourhood. The decision variables are affected by historical data. For the TBM this is the evidence of past damages of failures of TBM. For the background information we also use geographical data, such as the evidence of past collisions with underground utility networks in the area, and past damages to adjacent buildings. For two decision variables we introduced the ability to use the risk mitigation measures in the form o, such as adjusting the pace of construction work by TBM to the prevailing ground conditions – M1, and continuous updating of the information about the distribution of underground networks – M2. Mitigation actions aim at minimising the probability the occurrence risk events.

Symptoms of selected risk events are typically observed deviations of some parameters from accepted value ranges. In the example were used four symptoms/observations: subsidence of buildings under construction – S1, deviation of TBM parameters from the normal values – S2, vibration of neighbouring buildings – S3, and the subsidence of structural elements in adjacent structures – S4. New evidence concerned with these symptoms, i.e., observations of deviations of the parameters from the accepted ranges, may be introduced into the network and then back-propagated through the net, resulting in new (a posteriori) probabilities of risk events.

The information contained in the utility table, also called a matrix of costs and profits, was established on the basis of expert knowledge and is coded in the Bayesian Network as a table of payments (satisfaction) for various combinations of decision variables using the scale from 0 to 20, where 0 means the highest losses, for the case of deciding to continue the drilling when all the risk events take place, and 20 represents the largest gain for the decision to continue drilling in the absence of all risk events . The utility table is shown in Table 1.

Table 1. The utility table for technical risk, source: own study, http://www.norsys.com/download.html

Damage of TBM	Collisions with underground utility networks	Damage to buildings in the neighbourhood	Decision - whether to continue the work?	SATISFACTION
YES	YES	YES	YES	0

YES	YES	YES	NO	18
YES	YES	NO	YES	4
YES	YES	NO	NO	17
YES	NO	YES	YES	5
YES	NO	YES	NO	16
YES	NO	NO	YES	13
YES	NO	NO	NO	8
NO	YES	YES	YES	9
NO	YES	YES	NO	15
NO	YES	NO	YES	14
NO	YES	NO	NO	7
NO	NO	YES	YES	19
NO	NO	YES	NO	6
NO	NO	NO	YES	20
NO	NO	NO	NO	1

The presented diagnostic-decision support model in the form of a Bayesian Network provides a general organisational and technical view of the problem. It includes just three selected risks from a much more numerous group of risks related to the construction of the tunnel and therefore is substantially simplified. Individual nodes represent random variables of the problem, directed arcs show the relationships between the variables. Each child-node has associated with it a table of conditional probabilities that represents the strength of the impact on a given variable by its predecessors (parents) in the graph. The construction of the network (presented on Fig. 1) took place in the following order:

- variables of the model (graph nodes) and the connections among them were defined,
- a priori probabilities of the nodes without parents (e.g., evidence of past damages of TBM) were estimated,
- conditional probability tables and the utility table we encoded (network parameterisation).

Now the network was ready for the investigation of the impact of monitoring data and mitigation actions. The main purpose of this D-DSM model is to demonstrate the usefulness of BBNs for this type of problems. As a result of the model's application, it is possible, for example, to determine the cost associated with making a particular decision depending on the evidence from our monitoring system, and mitigation actions.

3. Information relating to the network shown on Figure 1

3.1. Damage of Tunnel Boring Machine

The risk of TBM damage refers to cases in which the effect is to exclude it from work for more than seven days, which can mean a failure to meet the project deadline. The following methods are proposed to identify this risk: the use of georadars (GPR) with continuous monitoring of their readings, control of soil excavated by TBM, control of timeliness and scope of inspection and maintenance of TBM.

According to Fig. 1 the logic of connections in the network must be understood in the following way: an event regarding evidence of past damages of TBM as a historical data was established for the two states: YES - the damage to the machine occurred in the past, NO - the damage did not occur for similar projects (shown in Table 2). For each of these variants are assigned the probability values included in the table of conditional probabilities.

Tab. 2a. Summary of input data for the risk of damage of TBM, source: own study

Evidence of past damages of TBM	M1. Adjustment the work tempo to the ground conditions	Damage of TBM - YES	Damage of TBM - NO
YES	YES	55	45
YES	NO	75	25
NO	YES	10	90
NO	NO	50	50

Tab. 2b. Summary of input data for the risk of damage of TBM, source: own study

Damage of TBM	S1. Subsidence of buildings under construction -YES	S1. Subsidence of buildings under construction - NO
YES	70	30
NO	25	75

Damage of TBM was established for two states (YES and NO). The state YES means that malfunctioning of TBM is expected. The state NO means the opposite.

As for the mitigating action, whose goal is to reduce the probability of the TBM damage, it is proposed to adjust the pace of the TBM tunnelling work to the type of soil. The variant YES means the introduction of the mitigating measure.

The observations indicating that there is potential for the TBM damage are the deviations of the measured values from the permitted levels for the subsidence of the project under construction. There are two states: YES - unexpectedly high subsidence of the tunnel was observed, NO - the subsidence is below the higher limit. Introducing the new information into the observation node leads to the evidence back propagation and to updating the probability of of the TBM damage.

The decision node “whether to continue carrying out works during the drilling of a tunnel” has two states YES and NO (Fig. 1). The expected utilities of state YES and NO may be estimated using the utility table and the updated (a posteriori) probabilities of decision variables. Needless to say, one selects the decision with the highest expected utility.

3.2. Collisions with underground utility networks

The risk of collision with underground networks relates to the potential of encountering unregistered underground utilities, which results in having to move them, and in turn leads to extended project time and increased costs. The following methods of identifying this potential based on the available historical information are proposed: a survey with utility providers, and interviews with neighbourhood residents.

To collect an early - warning information, it is proposed to monitor TBM works. As the mitigating action (decreasing the probability of appearance a risk of collision with networks) it is proposed to carry out continuous monitoring of the area during operations. For the collision event there are two states: YES - there will be a collision, NO - no collision is expected; the probability values for the parent node (past evidence) were assigned based on expert opinion.

3.3. Damage to buildings in the neighbourhood

The risk of damage to existing adjacent buildings is concerned with cases for which there is a need to perform additional work or to change the work technology, which in turn may lead to prolongation of work and cost increase(e.g., due to compensation payments to the owners of neighbouring buildings). There are proposed the following methods to diagnose this risk: standard geodetic monitoring, i.e., monitoring land subsidence . In addition we suggest monitoring the vibration characteristics and the technical state of neighbouring and potentially affected objects.

It is proposed that the measuring devices to be installed to collect data for at least two months before the start of construction work, and monitoring was continued for one year after the completion of the construction. It is proposed that the monitoring was conducted in three zones of influence of construction:

- zone 0 - located directly above the tunnel;
- zone 1 - located within the direct impact of the tunnel on buildings;
- zone 2 - located within an indirect impact of the tunnel on buildings (zone of secondary interactions).

The range of each zone is determined by the depth of drilling (foundation level of floor foundation slab) and the type of soil/land in the area of carried excavation.

The appearance of damage to the existing neighbouring facilities may require realisation of additional replacement works due to the change of soil and water parameters in relation to those accepted at the design stage of works. It is proposed to reduce the rate of the works depending on the information obtained as a result of the facilities monitoring.

For damage to buildings in the neighbourhood there are two states: YES - means the occurrence of damage to neighbouring buildings, NO - no damage. The probability values for parent node (historical damages) are based on expert opinion.

4. Evaluation of information Value

An important advantage Bayesian Network models is the ability to estimate the value of any monitoring/test information. One of the most important goals of the monitoring design process is to determine what information is worth collecting. This decision clearly depends on the cost of collecting the information (testing) and the information value.

Fig. 1 shows several possible observations that can be used to update the probabilities of the main decision variables. To compare the information value in this article we selected two observation types regarding the risk of damage to neighbouring buildings. The first observation is to monitor the vibrations in neighbouring buildings, while the other is to measure their subsidence.

Assuming that the cost collecting either information is the same, we want to choose the one that has a greater value. There are two methods for estimating this value.

One is to estimate the Expected Value of Sample Information (EVSI), which is frequently used for the selection of observations, particularly when the decision utilities are well known. The second method is to estimate the expected conditional reduction of the information entropy, conditioned on the information. The information that gives us greater reduction also more significantly reduces the uncertainty associated with the diagnostic variable. This simply means that we can diagnose our problem with more certainty. Calculations schemes for EVSI and entropy are shown at work [10].

Using the Bayesian Network shown in Fig. 1, it can be shown that the EVSI for the observation of vibrations in adjacent objects during TBM operation is given by:

- $EVSI_1 = (0{,}567*11{,}24+0{,}433*12{,}06) - 11{,}34 = 0{,}255$.

While for another observation (say, subsidence of adjacent buildings), the EVSI is:

- $EVSI_2$= (0,601*11,55+0,399*12,51) – 11,34= 0,593.

Using the EVSI criterion one would the select to monitor the subsidence.

Now let us consider the entropy criterion. For the network shown in Fig. 1 we have the conditional entropy reduction given observations of vibrations equal to:

- $\delta H(X/Y)_1$=0,065.

And the conditional entropy reduction for the second parameter is:

- $\delta H(X/Y)_2$=0,154.

In this case both criteria show that the observation of vibrations in adjacent objects during TBM operation is more valuable. In a general case, one has to decide whether the utility-measured value or the diagnosis uncertainty reduction is more relevant to the project

5. Summary

A multitude of methods and approaches to risk management process in construction projects points to the fact that the important element of the contractor activities is to make optimal decisions taking into account probabilities of potential risk events. Decisions regarding this issue should be taken as a result of carrying out risk management process, in which a very important starting point is to consider the risk events associated with the project, as well as their sources, symptoms, and mitigation actions. It has to be underlined that due to the clear graph form of the BBN model, the process of constructing such a model is transparent and very easy to follow. Therefore a group of experts during model development can focus on analysing relevant relationships that are to be encoded in the model, instead of endlessly arguing about their individual conclusions.

By modelling the risk sources one can consciously evaluate how the source disturbance will affect the final result. BBNs can be easily used to evaluate and compare the effects of various mitigation actions.

Finally, Bayesian Net models can be employed to support the monitoring system design process, by letting one evaluate the value of information, either from the expected utility view point, or by considering the uncertainty reduction of the events of interest.

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