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Probabilistic assessment of tunnel construction time using dynamic Bayesian network

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Abstract

Construction time estimates are important parameters for decision-making in transport infrastructure projects. At present, the construction time is usually assessed deterministically by experts; probabilistic models are not commonly employed in practice. A main reason is that the existing models often do not provide a realistic estimate of the overall uncertainty. In this contribution, we present a Dynamic Bayesian Network (DBN) model, which aims to more realistically represent the uncertainties in tunnel construction time estimates and which provides an understandable graphical representation of the model assumptions. The model considers the geotechnical uncertainties as well as uncertainties associated with human and other external factors. It includes the common variability of the construction performance and the occurrence of extraordinary events (failures) such as tunnel collapses. Analyses of construction performance data from tunnels constructed in the past provide a basis for estimation of failure rate and for determination of unit time distribution, which are the essential inputs of the probabilistic model. A case study demonstrates the applicability of the DBN model and the possibility of updating predictions with new information obtained during the construction process.

Keywords: Construction time, risk analysis, Dynamic Bayesian Networks, construction performance, failure rate, probabilistic model.

1 INTRODUCTION

Estimates of tunnel construction time and costs are highly uncertain. This uncertainty originates in the unknown geotechnical conditions, in natural variability of the construction performance and in unpredictable influence of common factors such as quality of planning, quality of construction management and external political and economical factors. Today, the construction cost and time are typically assessed deterministically. The deterministic estimates are, however, often underestimated, as shown for example in Flyvbjerg et al. (2002). This systematic underestimation of project cost and time causes severe problems to the construction industry and to society in general, because it does not provide a realistic information basis for decision-making (Hägler, 2012). The uncertainty of the construction time and cost estimates should be quantified and communicated with the stakeholders and with the public. The need of probabilistic prediction of construction time has been recognized in the tunnelling community in recent years (Lombardi, 2001; Reilly, 2005; Grasso et al., 2006; Edgerton, 2008).

Different approaches exist for analysing the risks and for assessing the uncertainty in the construction time and cost estimates. The existing models and approaches are summarized in Špačková (2012), where the advantages and limitations of the models are also discussed. In this paper we briefly describe a model using Dynamic Bayesian Networks (DBNs) for probabilistic modelling of the tunnel construction time, which was originally proposed in Špačková and Straub (2013) and Špačková et al. (2013). The first paper focuses on the algorithm for evaluation of the DBN, the later paper discusses a methodology for statistical analysis of data from past projects, which should be used for learning the parameters of the model. The model is suitable for utilization in all phases of the project: in early planning phases it provides a rough estimate based on limited amount of information and in later phases the estimate can be continually updated with new information, also during the construction itself.

2 DBN MODEL OF TUNNEL CONSTRUCTION TIME

DBN model of tunnel construction process is displayed in Figure 1. Each slice of the DBN represents a tunnel segment of length Δl (here $\Delta l = 5m$). The ith slice thus represents a tunnel segment between position $(i-1)\Delta l$ and $i\Delta l$. All variables are modeled as constant within a segment, i.e. the model implies that the geotechnical conditions and construction performance do not change within a segment. The individual variables of the DBN are summarized in Table 1 and described below.

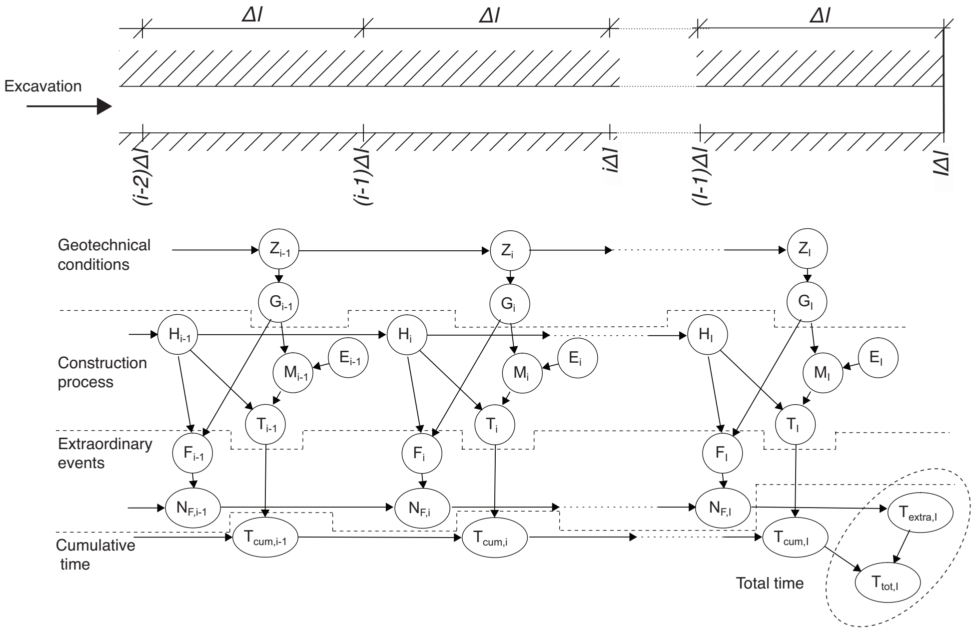

Figure 1: DBN model for tunnel construction process. The variables of the model are summarized in Table 1.

The geotechnical conditions are modelled by variables *zone* and *ground class*. **Zone** Z_i represents the locations of the quasi-homogenous geotechnical zones along the tunnel axis. **Ground class** G_i describes the geotechnical conditions in the ith segment, it correspond to the commonly used geotechnical classification systems (RMR, Q-system) or to a project specific classification. In this paper, ground class is defined deterministically for given zone.

Construction performance is modelled by variables human factor, geometry, construction method and unit time. **Human factor** H_i, which represents the common factors influencing the construction performance, is in one of the three states "unfavourable", "neutral" or "favourable" throughout the entire tunnel construction, i.e. the H_is are fully dependent from one slice to the next. **Geometry** E_i models different cross-sections along the tunnel (a typical cross-section vs. extended cross-section for emergency parking places EPP), the special conditions at the beginning and end of the tunnel and at the location where the tunnel passes an existing chemical plant. **Construction method** M_i describes the excavation type and the related support pattern applied in the ith segment and it is defined conditional on the ground class G_i and tunnel geometry E_i. For every construction method M_i and human factor H_i, the **unit time** T_i (i.e. time needed at excavation of the ith segment, an inverse of commonly used advance rate) is defined by a conditional probability distribution, $f(t_i|m_i, h_i)$, which should ideally be determined from analysis of data in past tunnels. To facilitate the application of the exact inference algorithm suggested in Špačková and Straub (2013), the variable T_i is discretized.

Table 1: Summary of variables of the DBN model.

Id.	Variable	Type	States of the variable
Z	Zone	Random/ Discrete	1,2,…,7
G	Ground class	Random/Discrete	3,4,5
H	Human factor	Random/Discrete	Favourable, neutral, unfavourable
E	Geometry	Determ./Discrete	37 m^2, 43 m^2, 46 m^2
M	Construction method	Random/Discrete	3-37, 3-43, 3-46, 4-37, 4-43, 4-46, 5-37, 5-43, 5-46
T	Unit time	Random/ Discretized	0, t_{int}, $2t_{int}$, …, 14.5 [days] *
F	Failure mode	Random/Discrete	Failure, No failure
N_F	Number of failures	Random/Discrete	0,1,2,3,>4
T_{cum}	Cumulative time	Random/Discretized	0, t_{int}, $2t_{int}$, …, 1392** [days]
T_{extra}	Delays caused by failures	Random/ Discretized	15, t_{int}, $2t_{int}$, …, $t_{extra,99.9}$ [days] ***
T_{tot}	Total time	Random/ Discretized	0, t_{int}, $2t_{int}$, …, $(1392 + t_{extra,99.9})$[days]

* t_{int} is the discretization interval of time variables, $t_{int} = 0.5\ day$,

** upper bound of cumulative time = 96 x 14.5= (number of segments) x (upper bound of unit time)

*** $t_{extra,99.9}$ is the 99.9 percentile of T_{extra}

The model also takes into account the occurrence of extraordinary events (failures of the construction process), i.e. events that stop the excavation for 15 or more days. These are modelled by variables failure mode and number of failures. **Failure mode** F_i represents the possible occurrence of an extraordinary event in segment i, it is defined conditionally on H_i and G_i. The probability of failure occurrence is determined based on failure rates observed in the past tunnels. **Number of failures** $N_{F,i}$ represents the total number of failures from the beginning of the tunnel up to the segment i.

The main output of the model is the **total construction time**, T_{tot}. In the DBN, it is computed as the sum of construction time excluding extraordinary events, T_{cum}, and the time delay caused by extraordinary events, T_{extra}. **Cumulative time** $T_{cum,i}$ is the time needed for the excavation of the tunnel up to the location $i\Delta l$. It is defined as the sum of $T_{cum,i-1}$ and the unit time in segment i, T_i: $T_{cum,i} = T_{cum,i-1} + T_i$. $T_{extra,i}$ is the time **delay due to occurrences of failures** (extraordinary events) in the tunnel construction up to the segment i. Assessment of the total construction time, T_{tot}, is in most cases of interest for the tunnel as a whole or for a section of the tunnel. Therefore, it is computed only at the end of the tunnel, in slice I, as illustrated in Figure 1.

Definition of variables ground class, construction method, geometry, unit time and cumulative time follows the procedure originally proposed for the Decision Aids of Tunnelling (DAT) model (see e.g. Einstein, 1996). Similar modelling of failure occurrences was originally used in Sousa and Einstein (2012).

3 NUMERICAL EXAMPLE

DBN model is applied to a 480 m long Czech tunnel, which was built as a part of an underground extension project. The tunnel has only one tube. The first section of the tunnel serves as an access tunnel and it will not be utilized after the completion of the project. The remaining section of the tunnel will be used as a ventilation plant and as a dead-end rail track. The New Austrian tunnelling method (NATM) was used for construction of the tunnel. The tunnel is constructed in homogeneous conditions of sandstones and clay stones. Based on the geotechnical survey, the tunnel is divided into seven quasi-homogeneous zones, the geology is categorized into three ground classes.

The resulting estimates of construction time are presented below. First the prior estimate from a planning phase is shown in Figure 2, second the updated estimate with performance observed during the construction of the first 150 m of the tunnel is shown in Figure 3.

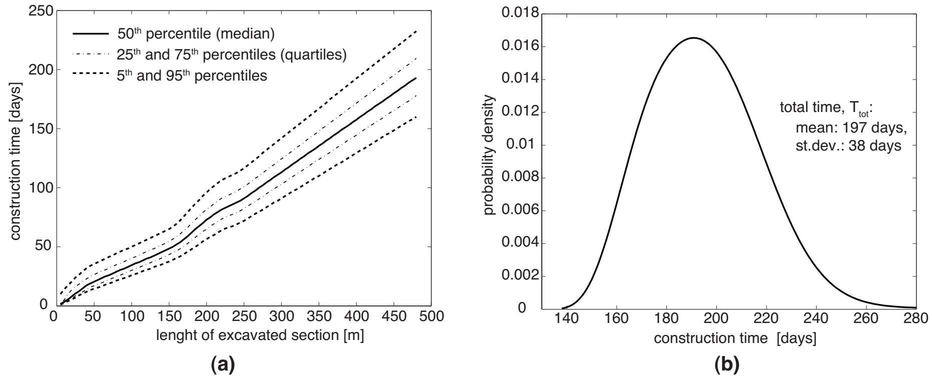

Figure 2: Prior prediction of the tunnel construction time: (a) Uncertainty in the estimated excavation progress (b) Probability density function (PDF) of total construction time for the whole tunnel.

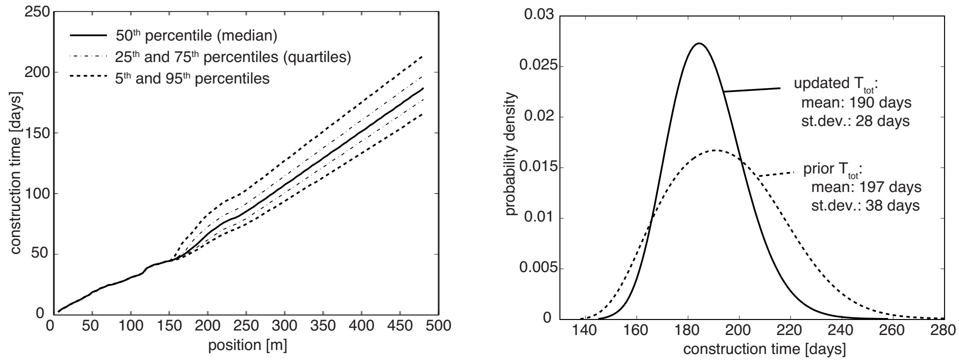

Figure 3: Updated prediction of the tunnel construction time: (a) Uncertainty in the estimated excavation progress (b) Probability density function (PDF) of total construction time for the whole tunnel.

In the Bayesian updating process, the conditional probability distribution of unit time $f(t_i|m_i, h_i)$ is also updated. An example of the prior and updated probability mass function (PMF) for construction method 3-37 and $H_i = "neutral"$ is shown in Figure 4.

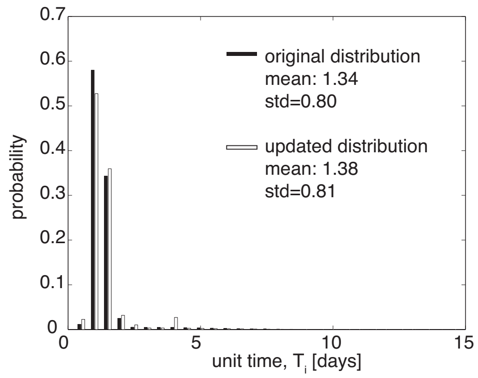

Figure 4: Prior and updated PMF of unit time per 5 m for construction method 3-37, $H_i =$ "$neutral$".

4 DISCUSSION AND CONCLUSION

A Dynamic Bayesian Network (DBN) model for probabilistic estimation of tunnel construction time originally proposed in Špačková and Straub (2013) and Špačková et al. (2013) is briefly described. Its utilization is illustrated on an application example of a Czech tunnel. For the prior prediction during the design phase, the parameters of the DBN model are determined by expert assessments informed by the statistical analysis of data from past tunnels. During the construction, the prior prediction is updated based on the observed performance. Also the model parameters, such as unit time, are updated with this new information. The results show that the proposed DBN model allows one to more realistically assess the uncertainty in the construction process.

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