Case Study

Construction Cost and Duration Uncertainty Model: Application to High-Speed Rail Line Project

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Abstract: Transportation construction projects are often plagued by cost overruns and delays. Applying contingencies and estimating risks at the project level often do not capture the multiple uncertainties in the construction process of large transportation projects. Thus, there is a need for innovative approaches and tools to avoid large construction cost and duration overruns. To counteract such underestimations, a construction model and an uncertainty model are developed. In the construction model, the construction of the four main types of structures in rail lines (tunnels, viaducts, cuts, and embankments) is modeled bottom-up from the single activity to the entire rail line. In the uncertainty model, three sources of uncertainty (variability in the construction process, correlations between the costs of repeated activities, and disruptive events) are modeled jointly at the level of the single activity. In a Monte Carlo simulation environment, these uncertainties are propagated to the total construction cost and duration through the combination of the individual activity costs and durations. The construction and uncertainty models are incorporated in the decision aids for tunneling (DAT), which have been extended beyond tunneling to consider these different structures and uncertainty types. All this was applied in the Portuguese high-speed rail project, in which historical data and expert estimations were used to model the cost and duration uncertainty. This application allowed validation of the model and then illustration of a variety of effects: the three sources of uncertainty produce different cost and duration impacts depending on the type of structure, suggesting structure-specific mitigation measures. Most importantly, their cumulative impact causes significant increases in construction cost and duration of the modeled rail line compared with the deterministic estimates: specifically, 58% in the construction cost of tunnels, and 94% in the construction duration of cuts and embankments. The proposed construction and uncertainty models contribute and advance the body of knowledge: For the first time, variability, correlations, and disruptive events are quantitatively modeled in one simulation environment, and the impact of these uncertainty sources can be assessed jointly and compared. The proposed models also significantly contribute to practice by providing transportation agencies with a modeling tool to tackle cost and duration uncertainty in the construction of rail lines and other linear or networked infrastructure projects. **DOI:** **10.1061/(ASCE)CO.1943-7862.0001161.** © *2016 American Society of Civil Engineers.*

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Introduction

Cost and duration underestimations are widespread in the construction of transportation infrastructure projects. Two examples of cost and duration underestimation in transportation infrastructure projects are the Big Dig in Boston and the Channel Tunnel between England and France. In 1990, it was estimated that the Big Dig in Boston would cost $6 billion and would be completed by 2001. The project included a contingency for unidentified risks of $100 million, which is just 1.7% of the estimate cost. Unfortunately, the project cost almost tripled to a total of nearly $15 billion and was completed only in 2007 (Salvucci 2003). The construction of the Channel Tunnel started in 1988, the project took approximately 20% longer than planned (6 years instead of the planned 5) and came in 80% over budget (costs increased £2 billion, from £2.6 billion forecast to £4.6 billion). The Big Dig and the Channel Tunnel are just two among many examples of transportation infrastructure projects completed with large cost and duration overruns. While these projects are very large, the phenomenon of cost overruns and delays in transportation projects is widespread as described by Flyvbjerg et al. (2002). The average cost escalation of the 258 analyzed transportation infrastructure projects was 27%. For the subset of rail line projects, the average cost escalation reached 45%.

In this paper a combined construction and uncertainty model will be described with which cost and duration underestimation can be avoided. The model will be applied to a section of the proposed high-speed rail network in Portugal, the Rede Ferroviária de Alta Velocidade (RAVE), the Portuguese high-speed railroad, to validate it and to show its practical applicability.

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Background

This section summarizes and analyzes possible causes and remedies of cost and duration overruns in the construction of civil infrastructures specifically for transportation. For reasons of space and relevance to what is presented in this paper, the background information and thus the references concentrate on transportation infrastructure. More details on causes and remedies can be found in Moret (2011).

Flyvbjerg et al. (2002) and Flyvbjerg (2007) proposed three explanations for the widespread occurrence of cost underestimation in transportation infrastructure projects: technical (estimation errors), economic–political (economic self-interest and economic public interest), and psychological (optimism bias). Technical errors can be limited or eliminated through better forecasting techniques, improved data, and experienced forecasters. Economic–political reasons can be reined in by measures of accountability. Optimism bias can be avoided with simple reality checks and by using debiasing techniques.

Flyvbjerg (2006) proposed applying reference class forecasting to transportation construction projects; this is a methodology developed in the fields of psychology and management (Lovallo and Kahneman 2003). This tool estimates the performance, e.g., cost or duration, of a project based on statistical analyses of past projects (outside view) rather than on the specifics of the project itself (inside view). In three steps Flyvbjerg (2006) identifies a reference class of past similar projects, derives a cost and/or a duration probability distribution (reference class distribution), and compares the project with the reference class distribution in order to estimate the most likely cost and/or duration.

Risk factors causing project cost underestimation have been described in detail in the transportation construction literature (Anderson et al. 2007; Molenaar 2005; WSDOT 2005; Caltrans 2007; FTA 2004). Among these, Anderson et al. (2007) describe 11 factors from internal sources (bias, wrong delivery and procurement approach, project schedule changes, engineering and construction complexities, scope changes, scope creep, poor estimations, inappropriate contingencies, faulty execution, misunderstanding between agency and contractual parties, and contract document conflicts) and seven factors from external sources (local concerns, inflation, externally driven scope changes and scope creep, lack of competition for a project, unforeseen events, and unforeseen conditions). In order to counteract the risk factors causing cost underestimation in transportation, Anderson et al. (2007) propose eight strategies: (1) cost management strategy, (2) scope and schedule strategy, (3) proactive engagement of external stakeholders, (4) risk strategy, (5) delivery and procurement strategy, (6) document quality strategy, (7) improved accuracy and consistency, and (8) minimization of outside influence. For the purpose of this paper, the focus is on the risk strategy, which consists of five phases: identification, assessment and analysis, mitigation, allocation, and monitoring.

In construction projects, the assessment of cost and duration risk has been tackled in three main ways: percentage contingency, qualitative estimation methods, and quantitative estimation methods. Contingency application, being the more basic approach, can be improved by using qualitative estimation methods, e.g., risk × impact matrices, among others, to identify significant risks and qualitatively assess their impact. Quantitative estimation methods are better than qualitative ones (assuming the availability of real input data) because they can quantify the impact of risks. A variety of quantitative estimation methods have been used to estimate construction costs: genetic algorithms (Li and Love 1997; Feng et al. 1997; Zheng et al. 2004), regression modeling (McCaffer et al. 1984; Newton 1991; Trost and Oberlender 2003), fuzzy theory (Paek et al. 1993; Tah and Carr 2000; Dikmen et al. 2007), neural networks (Yeh 1998; Kim et al. 2004), and Monte Carlo simulations (Touran and Wiser 1992; Chau 1995; Moret and Einstein 2012b), among others. The model proposed here is a Monte Carlo simulation tool. Applications of Monte Carlo estimation methods continue to evolve, and the proposed model advances and adds value in this ongoing development.

The proposed model advances existing Monte Carlo estimation models by quantifying variability, correlations, and disruptive events (also known as risk events) in one simulation environment. For the first time, the impact of these uncertainty sources can be assessed jointly and compared. In project construction there are several uncertainties. Variabilities in cost and duration—or cost and schedule risk—are usually considered in risk modeling in construction. The variability in duration, or schedule uncertainty, can be modeled with the program evaluation and review technique (PERT) (U.S. Department of the Navy 1958), the advanced programmatic risk analysis and management model (APRAM) (Dillon and Paté-Cornell 2001), and the construction schedule risk analysis model (CSRAM) (Ökmen and Öztas 2008). Some of these tools can also model variability in project cost. With the decision aids for tunneling (DAT) (Einstein 2004), both variability in duration and cost of tunnel projects can be evaluated (Einstein 2001; Min 2008). Correlations are a second type of uncertainty that occurs in construction processes. Correlations between variables in construction projects were modeled by Touran and Wiser (1992), Ökmen and Öztas (2008), and Moret and Einstein (2012b). For instance, correlations exist between the costs of a unit length of tunnel and the next unit length of tunnel, and between the costs of constructing a viaduct pier and its foundation. A variety of construction correlations and thus the just mentioned correlations were investigated in Moret and Einstein (2012b). Disruptive events are a third type of uncertainty occurring in construction. These have been discussed extensively by Sousa (2010). The Cost Estimate Validation Process (CEVP) developed by the Washington State Department of Transportation (2008) models risk events, defined by their probability of occurrence and their cost and/or time impact.

The proposed model advances existing models because it can quantify in one simulation environment (1) variability, (2) risk events (disruptive events), and (3) correlations. For the first time, the impact of these uncertainty sources can be assessed jointly and compared. There is consensus that tools such as PERT, APRAM, and CSRAM add value by quantifying the impact of cost and duration variability. It is recognized that CEVP is a superior tool because it can quantify the impact of disruptive events, also known as risk events. It has been shown that cost correlations have an impact on construction costs, and this impact has been modeled quantitatively. However, none of these existing models can treat at the same time variability, risk events, and correlations, compare their individual impacts, or assess their cumulative impact. For the first time, the proposed model makes it possible to quantitatively model these three sources of uncertainty and their impact on project cost and duration.

The proposed model is different from the existent construction simulation tools in that it not only can model complex construction projects but it also can model the impact of different types of risks on project duration and cost. Construction simulation or project simulation in a wider sense exists since computers became widely used in engineering, i.e., in the 1960s. Specific simulation tools with which not only interrelationships of different activities but cost and time could be estimated started being developed in the early 1970s. Without claiming completeness in referring to this history, it is necessary to mention the highway cost model (Moavenzadeh et al. 1972) and the tunnel cost model (Moavenzadeh et al. 1974) as well as CYCLONE (Halpin and Woodhead 1976) as early construction simulation models, with the last being more general than the other two. This was followed by enhancements such as INSIGHT (Paulson 1978), RESQUE (Chang 1986), UM-CYCLONE (Ioannou 1989), and Micro-CYCLONE (Halpin 1990). Significant advancements in construction simulation tools were introduced with CIPROS (Odeh 1992), STROBOSCOPE (Martinez 1996), RBM (Shi and AbouRizk 1997), LBS (Oloufa and Ikeda 1997), and Symphony (Hajjar and AbouRizk 2002). The more advanced of these simulation tools allow one to develop complex construction models and they include flexible user interfaces. However, the treatment of uncertainties was limited in many of these tools (with the exception of the tunnel cost model). Software that can handle

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risk with the use of Monte Carlo simulation are *Oracle Primavera*, *Pertmaster*, *CrystalBall*, and *@Risk*. To different degrees, they allow one to model relatively simple construction projects—or complex projects at an aggregate level—and to estimate the impact of risks on project duration and cost. The proposed model is different from the existing ones in that it not only can model complex construction projects but it also can model the impact of different types of risks on project duration and cost. Also, the proposed model can do both things through a user-friendly interface and graphical representation of the project.

Thus, the proposed model advances existing Monte Carlo models and simulation tools for infrastructure construction in two ways. On the one hand, the proposed method models for the first time variability, correlations, and disruptive events in one simulation environment and their separate and cumulative impact. On the other hand, the simulation tool can both model the construction of complex projects, such as large infrastructure projects, and simulate risk in construction cost and duration.

Construction Model

In the construction model the construction cost and duration of a rail line (or other linear or networked infrastructure) are calculated as the sum of the costs of all activities and the durations of the activities on the critical path of the activity network. How activity networks are created and cost and duration are calculated are explained in this section.

Fig. 1. Tunnel construction; activity modeling the construction of one unit length of the tunnel

A rail line consists of a sequence of four main types of structures: tunnels, viaducts, cuts, and embankments. The construction model can represent any sequence of these structures, however, often a tunnel is preceded and followed by a cut, a viaduct is preceded and followed by an embankment, and cuts and embankments alternate with one another in a sequence of cuts and embankments. The networks and subnetworks were developed based on a detailed evaluation of the corresponding construction processes. Examples of the resulting networks are depicted in Figs. 1–3. The actual networks consisting of hundreds of activities are shown in Moret (2011). The construction of each structure is modeled with activities. These are organized in repeating subnetworks that are connected in structure networks, which in turn are connected in the network representing the construction of the rail line. Modeling the activity networks with arrows (rather than with activities on nodes) is determined by the graph-based simulation tool, the DAT (Einstein 2004), which has been expanded to model also viaducts, cuts, and embankments.

The construction of a tunnel is modeled with a one-activity subnetwork that includes all operations of excavating and supporting a unit length of tunnel (Fig. 1). The tunnel subnetwork is repeated as many times as the number of unit lengths in the tunnel [more complex tunnel networks could be used if needed, e.g., in Einstein (2001)]. An investigation of possible viaduct construction processes has been conducted in Moret (2011) from which the three typical processes (span-by-span, balanced cantilever, and launching) can be identified. Here only the span-by-span construction process is shown. The construction of a viaduct is modeled as the construction of its elements: abutments, pile sets, footings, piers, deck sections, technical blocks (soil improvement preceding and following a viaduct), and finishing. Each element is represented with an activity in the viaduct activity network. The subnetwork models a unit including the foundation, the pier, a dummy activity, and the deck section preceding the pier (Fig. 2). (the dummy activities used here and in the other subsequent networks could also be called limby—they involve no cost and time). The subnetworks

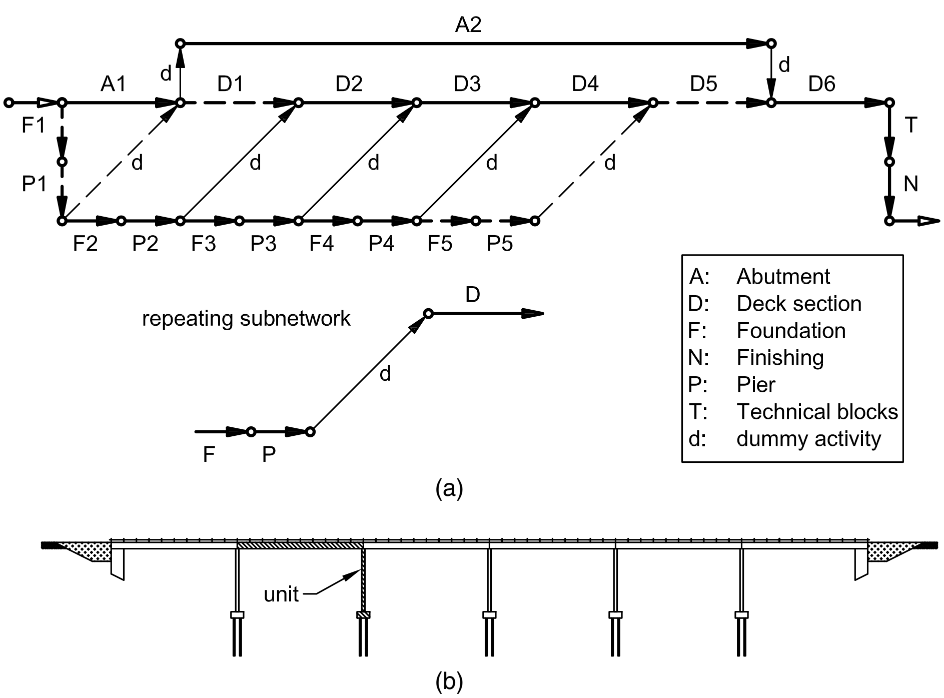

Fig. 2. Viaduct construction with span-by-span construction method: (a) activity network and repeating subnetwork of (b) a six-span viaduct

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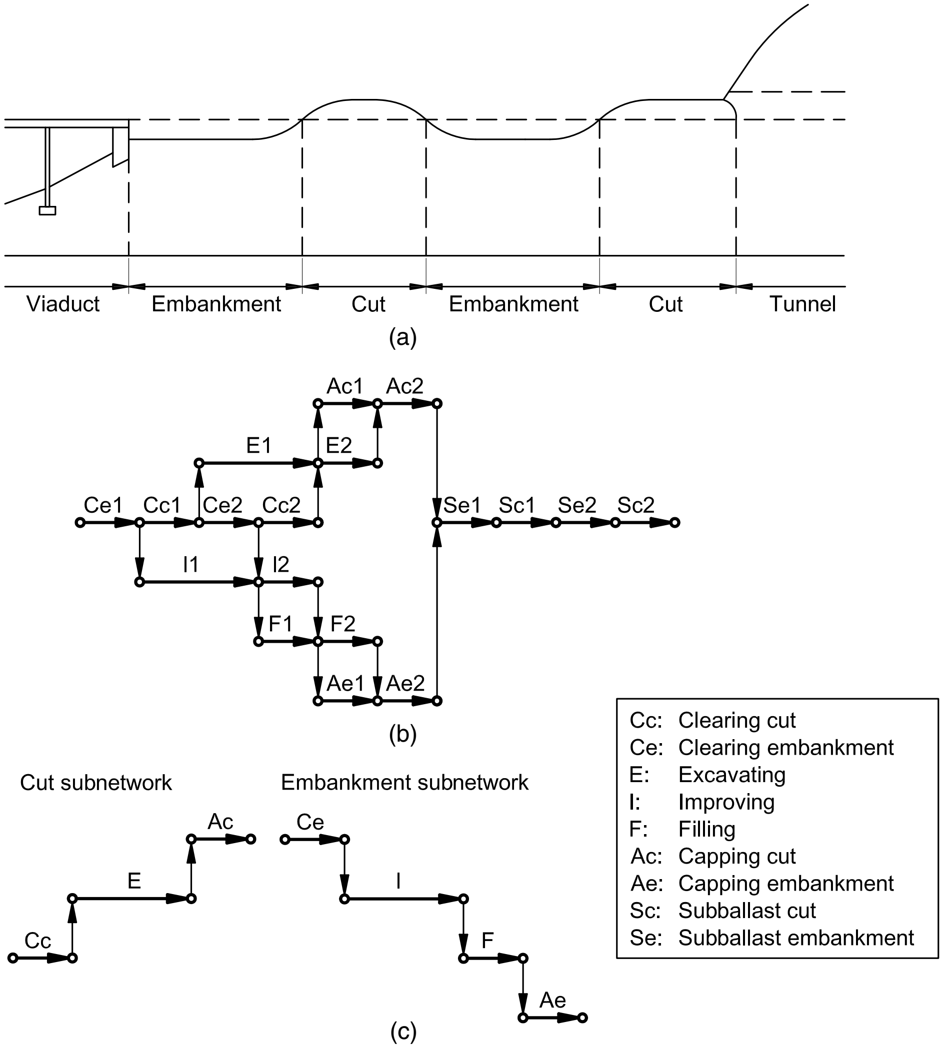

Fig. 3. Construction of cuts and embankments: (a) sequence of cuts and embankments, for instance, between a viaduct and a tunnel, modeled with (b) an activity network consisting of (c) repeated subnetworks; thinner arrows are dummy activities

are repeated as many times as the number of units, while the activities modeling the construction of abutments, technical blocks, and finishing are added at the beginning and at the end of the sequence of repeated subnetworks (Fig. 2). The construction of cuts and embankments is modeled jointly in an activity network including the following processes: clearing the soil, improving the in situ material, excavating the cut and filling the embankment, capping the structure, and placing the subballast. For cuts and embankments, two subnetworks are used (Fig. 3): the cut subnetwork (clearing, excavating, capping, and two dummy activities) and the embankment subnetwork (clearing, improving, filling, capping, and three dummy activities). The cut and embankment subnetworks are repeated as many times as the number of cuts and embankments. For all four types of structures, different activity networks can be constructed if desired. Activity networks can be combined depending on construction needs, e.g., in parallel for concurrent construction of structures or in sequence for subsequent construction of structures. An activity network can also be subdivided if, e.g., a tunnel is excavated starting from both ends.

Each activity in a network causes cost and requires time (activity duration). Examples of equations used to calculate activity cost and duration are in Table 1 [for a comprehensive list see Moret (2011)], which were made available by the engineering office responsible for the design of the high-speed rail line modeled in this paper (the numbers for the tunnel advance rate are very low, but the engineer's information was retained to be consistent). In the case of the cut excavation and the embankment fill, activities may include idle durations because embankments are usually filled with the material excavated in the cuts, where a mass balance between excavated and filled material is sought. This is modeled as follows: (1) the activity *filling* cannot start unless excavated material is available, and (2) the activity *excavating* cannot produce excavated material unless the embankment can receive it, i.e., after the clearing of the embankment is completed. For viaducts, it is assumed that a pier is constructed in parallel with a deck section, thus its construction duration is equal to zero because the deck section requires more time to be constructed.

The construction cost of the rail line is given by the sum of the costs of tunnel activities $t = 1, \ldots, n_t$, the costs of viaduct activities $v = 1, \ldots, n_v$, the costs of cut activities $c = 1, \ldots, n_c$, and the costs of embankment activities $e = 1, \ldots, n_e$ [Eq. (1)]. The construction duration of the rail line is equal to the sum of the activities $j = 1, \ldots, m$ on the critical path of the modeled networks [Eq. (2)]

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Table 1. Cost and Duration Equations for the Construction of Tunnels, Viaducts, Cuts, and Embankments

Structure	Cost equation	Duration equation
Tunnel	(Cost per unit length) × length	(Duration per unit length) × length
Medium geology	(12,050 Euro/m) × length	(0.6 day/m) × length
Viaduct	Element cost	Element duration
Deck $l > 35$ m; l: deck's span in meters	$(1{,}000 + 75l)$ Euro	14 days
Pier $l > 35$ m; h pier's height in meters	$[(12{,}000 + 2{,}000h) \times (0.4 + 0.022l)]$ Euro	0 day
Cut and embankment	(Cost per unit volume) × volume	Volume/(production rate)
Clearing	(1.25 Euro/m^3) × volume	Volume/(25,689 m^3/day)

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$$\text{Total Cost} = \sum_{t=1}^{n_t} \text{Cost}_t + \sum_{v=1}^{n_v} \text{Cost}_v + \sum_{c=1}^{n_c} \text{Cost}_c + \sum_{e=1}^{n_e} \text{Cost}_e \tag{1}$$

$$\text{Total Duration} = \sum_{j=1}^{m} \text{Duration}_j \tag{2}$$

Although construction may last several years, discount rates are assumed at 0%, but this can be done differently if so desired. For simplicity, cost escalation is also assumed at 0%.

Uncertainty Model

The construction cost and duration of a project are uncertain. The probability distributions of the total construction cost and duration of a rail line are estimated by modeling the sources of uncertainty at the activity level and propagating these through the activity network of the rail line.

The uncertainty model includes three sources of uncertainty at the activity level: cost and duration variability, cost correlations, and disruptive events. Through these three sources of uncertainty many risk factors can be modeled, as shown subsequently. If input data were not available for a source of uncertainty, probabilities and correlations were estimated by a tunnel expert, a viaduct expert, and an earthwork expert with more than 30 years of experience. Expert estimation of probabilities and correlations was done through a rigorous estimation process, detailed in Moret and Einstein (2012a).

Variability is the change in cost and duration variables under normal conditions, i.e., in a regular construction process, such as the variation of cost between excavating 1 m of tunnel and the next meter of tunnel in the same geology and construction environment. The variability in cost is modeled with the lognormal distribution because this often underlies the distribution of construction cost variables (Touran and Wiser 1992). Conveniently, the lognormal distribution is bounded at the minimum (cost variables are positive), skewed to the right, and has a thin upper tale. The variability in duration is modeled with the triangular distribution for four reasons: (1) it is closed-ended in the lower tail (duration variables are positive), (2) it can be either skewed to the left or to the right, (3) the minimum, mode, and maximum are relatively easily estimated by an expert (Moret and Einstein 2012a), and (4) the triangular distribution is often used in construction modeling (Chau 1995; Back et al. 2000; Haas and Einstein 2002). The input probability distributions of the tunnel, viaduct, cut, and embankment costs and of the tunnel durations (Tables 2–4) were made available by the engineering office responsible for the design of the high speed rail line modeled in this paper and RAVE. The input probability distributions of the viaduct, cut, and embankment durations (Tables 2–4) were estimated by the viaduct engineer and the earthwork engineer through the estimation process described in Moret and Einstein (2012a).

Costs in construction can be independent, and therefore uncorrelated, or correlated. Touran (1993) and Newton (1991) showed that costs were positively correlated and the standard deviation of the total costs was underestimated if cost correlations were disregarded. In the proposed model, costs are modeled as independent or positively correlated, e.g., tunnel construction costs are independent of the viaduct construction costs, while the cost of excavating a unit length of tunnel is positively correlated with the cost of excavating the next unit length of tunnel. In the uncertainty model, cost correlations are quantified with the Spearman correlation and modeled with NORTA (Cario and Nelson 1997). The choice of Spearman correlation coefficient over the traditional Pearson correlation coefficient is discussed in detail in Moret and Einstein (2012b). The choice of NORTA over other methods to model correlations between variables is also discussed in Moret and Einstein (2012b) and Moret (2011). In these publications, a thorough evaluation of which correlations affect cost and time of infrastructure projects was conducted. The impact on the construction cost and duration of five types of correlation were analyzed: (1) the correlation between the costs of different activities in a structure, for example the correlation between the cost of constructing a viaduct's pier and the cost of constructing its foundation, (2) the correlation between the costs of a repeated activity in a structure, e.g., the correlation between the cost of excavating the 10th meter and the cost of excavating the 11th meter of a tunnel, (3) the correlation between the costs of activities in adjacent structures, e.g., excavating a meter of tunnel and excavating a meter of cut at the tunnel's portal, (4) the correlation between the costs of same activities in same type of structures, e.g., excavating a meter of Tunnel A and a meter of

Table 2. Tunnel Construction Deterministic and Probabilistic Cost and Duration Input

Tunnel conditions	Cost per unit length (Euro/m)					Duration per unit length (day/m)				
	Deterministic	Minimum	Mode	Mean	98th percentile	Deterministic	Minimum	Mode	Mean	Maximum
Good geology	10,100	0	8,969	10,100	17,308	0.45	0.04	0.26	0.45	1.05
Medium geology	12,050	0	10,649	12,050	20,867	0.60	0.01	0.45	0.60	1.35
Poor geology	14,825	0	13,170	14,825	23,170	0.825	0.08	1	0.825	1.39

Note: Minimum, mode, mean, and 98th percentile of the lognormal distributions of the input cost per unit length and minimum, mode, mean, and maximum of the triangular distributions of the input duration per unit length for a tunnel in good, medium, or poor geology.

Table 3. Viaduct Construction Deterministic and Probabilistic Cost and Duration Input

Activity	Cost factor (–)					Duration (days)				
	Deterministic	Minimum	Mode	Mean	98th percentile	Deterministic	Minimum	Mode	Mean	Maximum
Prework	1.0	0.8	1.0	1.04	1.26	42	29	42	51.8	84
Abutment						56	43	56	70.3	112
Predeck with staging						28	19.4	28	33.0	56
Predeck with gantry						56	29.9	56	66.0	112
Deck section						14	8	14	16.7	28
Pier						0	—	—	—	—
Foundation footing						0	—	—	—	—
Foundation pile set						0	—	—	—	—
Technical block						28	20	28	34.5	56
Finishing						0.014/m	0.010/m	0.014/m	0.017/m	0.028/m

Note: Minimum, mode, mean, and 98th percentile of the lognormal distribution of the cost factor; minimum, mode, mean, and maximum of the triangular distributions of the viaduct durations.

Table 4. Deterministic and Probabilistic Construction Cost and Duration Input for Cuts and Embankments

Activity	Cost per unit volume (Euro/m^3)					Production rate (m^2/day or m^3/day)				
	Deterministic	Minimum	Mode	Mean	98th percentile	Deterministic	Minimum	Mode	Mean	Maximum
Clearing	1.92	0.96	1.92	2.05	2.88	20,234	12,141	20,234	20,234	28,328
Mechanical excavation (eight crews)	3.5	2.7	3.5	4.1	6.92	25,689	18,349	25,689	25,689	33,029
Blasting (eight crews)	8.08	5.05	8.08	9.31	15.15	7,951	6,116	7,951	7,951	9,786
Improving	4.85	4.04	4.85	5.04	6.06	25,689	18,349	25,689	25,689	33,029
Filling	1.25	0.94	1.25	1.42	2.19	25,689	18,349	25,689	25,689	33,029
Capping	6.75	4.5	6.75	7.06	9	4,205	3,823	4,205	4,205	4,587
Subballast	14.4	10.8	14.4	14.9	18	470	403	470	459	504

Note: Minimum, mode, mean, and 98th percentile of the lognormal distributions of the costs; minimum, mode, mean, and maximum of the triangular distributions of the production rates.

Tunnel B, and (5) the correlation between the cost and time of an activity. Correlation 2 has the greatest impact on total cost (Moret and Einstein 2012b). Therefore, the correlation between the costs of a repeated activity in a structure is modeled here.

The correlation between the costs of a repeated activity in a structure is modeled in tunnel, cut (excavating activity), and embankment (filling activity) construction. The cost correlations were estimated by the tunnel expert through the estimation process (Moret and Einstein 2012a). In viaduct construction, the costs of the repeated activities are assumed to be independent because the deck section length can vary from deck section to deck section, the pier height can vary from pier to pier, the foundations vary depending on the geology, and the two abutments and the two technical blocks are at the opposite ends of the viaduct [more details can be found in Moret and Einstein (2012b) and Moret (2011)].

A disruptive event, i.e., the third source of uncertainty in the uncertainty model, is an event with a large cost and/or duration impact and usually a small probability of occurrence, such as a flooding. Disruptive events are associated with three uncertainties: (1) the probability that the event occurs, (2) the cost uncertainty once the event occurs, and (3) the duration uncertainty once the event occurs. The occurrence of the disruptive event is modeled with a Markov process (Fig. 4), while the cost and duration impacts are modeled with the triangular distribution for the same reasons described previously for the duration probability distribution. Here two disruptive events are modeled per type of structure, however, more disruptive events can be easily modeled. The tunnel, viaduct, and earthwork experts identified the disruptive events and estimated the probability of occurrence and the distributions of cost and duration once the event occurs (Moret and Einstein 2012a). The identified disruptive events are:

- Tunnels: cave-in, water inflow;
- Viaducts: differing site conditions, construction accident or problem; and
- Cuts and embankments: flooding, differing site conditions.

The probabilities and impacts of these disruptive events were estimated by the experts and are summarized in Table 5.

The construction of the rail line and the uncertainty sources are simulated activity by activity in an adapted version of the simulation tool DAT (Einstein 2004). Through multiple Monte Carlo simulation runs, a distribution of the total construction cost and duration are obtained. With this simulation tool, the geologic uncertainty can be represented in three ways. The first possibility is through the choice of probability distributions when modeling variability, e.g., in the construction of the tunnels, different probability distributions of cost and duration are available to account for different ground conditions. The Monte Carlo simulation draws the cost and duration for the construction of a unit length of tunnel from the set of probability distributions corresponding to the encountered ground conditions. The second possibility is given by the disruptive events. In fact, four of the six disruptive events identified by the

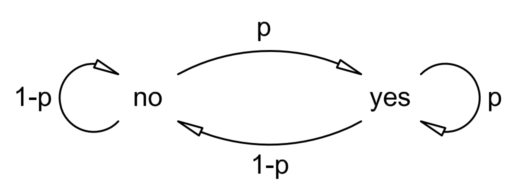

Fig. 4. Markov process: probability of occurrence (p) of a disruptive event (state: yes)

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Table 5. Probability of Occurrence and Probability Distributions (Triangular) of the Cost and Duration Impacts of Disruptive Events

Structure	Disruptive event	Probability of occurrence	Cost			Duration		
			Minimum	Mode	Maximum	Minimum	Mode	Maximum
Tunnels	Cave-in	1/800 m	0.2×10^6 euro	10^6 euro	10×10^6 euro	5 days	30 days	270 days
	Water inflow	1/500 m	0.05×10^6 euro	0.2×10^6 euro	10^6 euro	1 days	15 days	60 days
	Construction accidents/problems	1%	1%	15%	30%	7 days	60 days	365 days
Viaduct	Differing site conditions	5%	0%	20%	50%	2 days	60 days	240 days
Cuts and embankments	Flooding	1 year	0.15×10^6 euro	0.7×10^6 euro	2×10^6 euro	1 days	18 days	35 days
	Differing site conditions	50%	5%	—	30%	15%	—	100%

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experts are of a geologic nature. Third, the simulation tool DAT can model the uncertainty in the ground conditions, e.g., the uncertainty of the spatial extension of poor geology in the alignment. In the application of the construction and uncertainty models presented subsequently, the first and second possibilities were used to model geologic uncertainty.

Application of the Construction and Uncertainty Models to a Section of the New Portuguese High-Speed Rail Network

The construction model and the uncertainty model are applied to a 45.6-km-long section of the Portuguese high-speed rail between the northern cities of Porto and Braga (Alignment A in Fig. 5). It includes five tunnels, six viaducts, 22 cuts, and 22 embankments. First, the construction cost and duration were calculated using Eqs. (1) and (2) and the information provided by the design engineers and RAVE. This is real information as used in the actual project; this applies also to the cost and time distributions as mentioned previously. Construction cost and duration are 308.2 million-Euro and 6,589 days for the scenario that tunnels are constructed in sequence, viaducts are constructed in sequence, and cuts and embankments are constructed in sequence while tunnel construction, viaduct construction, and cuts and embankments construction are in parallel [Fig. 6(a)]. The total cost of just 300 million Euro may look small for such a large transportation project, but the construction costs considered here do not include the installation of the track, power and transmission lines, safety infrastructure, or signals.

Second, the construction model presented in this paper was applied to the Portuguese rail line and a simulation with no uncertainty sources (i.e., deterministic values) was run in DAT. The obtained construction cost and duration (308.2 million Euro, 6,589 days) match the preceding construction cost and duration. Thus, the construction model and the simulation in DAT were validated.

Then, uncertainties are simulated in DAT by adding to the construction process one source of uncertainty at a time: first variability, then cost correlations, and finally disruptive events. The impacts of the three sources of uncertainty are analyzed by comparing the deterministic construction cost and duration, as just obtained and discussed, with the mean construction cost and duration and the 90th percentiles of the construction cost and duration. The 90th percentile implies the chance of one cost overrun or one project delay in 10 projects, which is assumed to be acceptable.

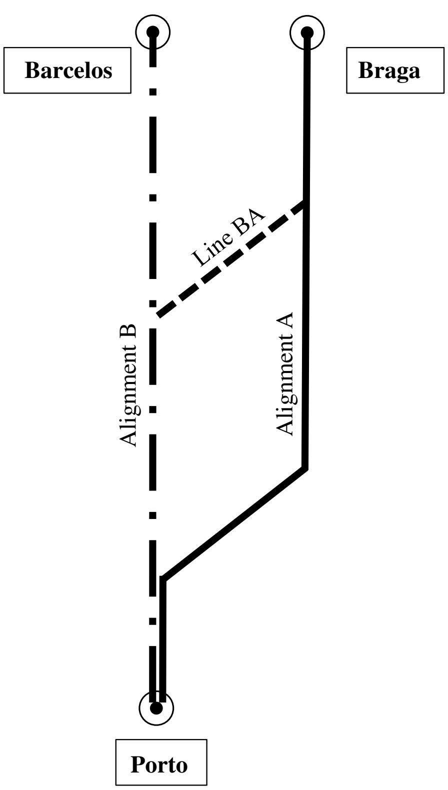

Fig. 5. Schematic map of the planned Portuguese high-speed rail lines north of Porto; Alignment A was studied in this paper; the distance between Porto and Braga is approximately 45–50 km

Variability

Variability in the input cost and duration creates the scattergram (gray cloud) of total cost and total duration in Fig. 7 (one gray dot for each simulation run): the scattergram shows the uncertainty in total cost and total duration caused by variability. For tunnels, the deterministic total cost and total duration, the black dot, is located in the center of the gray scattergram, while for viaducts, cuts, and embankments the deterministic total cost and total duration lie outside the gray scattergram. For tunnels [Fig. 7(a)], the deterministic total cost and total duration are equal to the mean total cost and the mean total duration because the deterministic input cost and duration per unit length are equal to the mean input cost and duration per unit length (Table 2). For viaducts, cuts, and embankments [Figs. 7(b and c)], the deterministic total cost and duration are smaller than the mean total cost and duration (Table 6) for the following reasons: First, the deterministic total cost and duration are the sums of the deterministic input cost and duration, which are equal to the modes of the input cost and duration distributions (Tables 3 and 4). Second, the mean total cost and duration are equal to the sum of the mean input costs and durations, respectively (e.g., Bertsekas and Tsitsiklis 2002). Third, input cost distributions are skewed to the right, i.e., the mode input cost is smaller than the mean input cost (Tables 3 and 4). Thus, the sum of the mode input costs is smaller than the sum of the mean input costs. Fourth, input

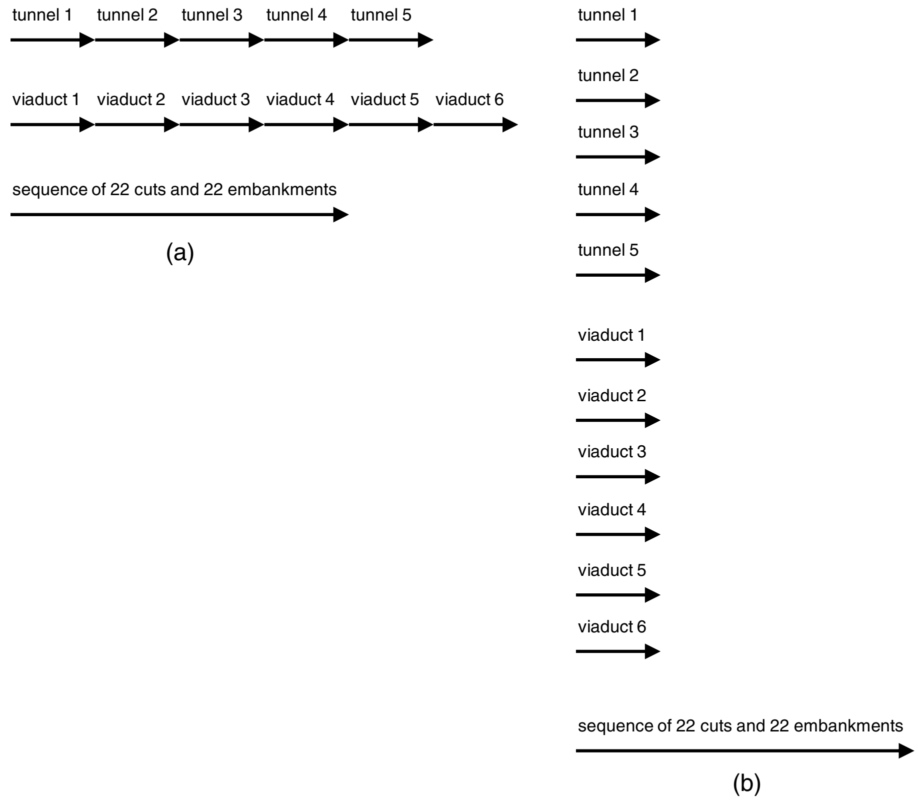

Fig. 6. Tunnels, viaducts, cuts, and embankments in (a) sequential; (b) parallel construction

duration distributions for viaducts are also skewed to the right, i.e., the mode input duration is smaller than the mean input duration (Table 3). Thus, the sum of the mode input durations is smaller than the sum of the mean input durations. Last, input production rate distributions for cuts and embankments are either symmetric or skewed to the left, i.e., the mode input production rate is equal to or larger than the mean input production rate (Table 4). However, because the construction duration is equal to the volume divided by the production rate, the sum of the construction durations calculated with the mode input production rates is smaller than the sum of the construction durations calculated with the mean input production rates. Therefore, for viaducts and cuts and embankments, the deterministic total cost and duration are smaller than the mean total cost and duration. Due to the skewness of the input distributions and the number of activities, the deterministic total cost and duration (black dots) are so much smaller than the mean total cost and duration (gravitational center of the gray cloud) that the black dots fall outside the gray cloud.

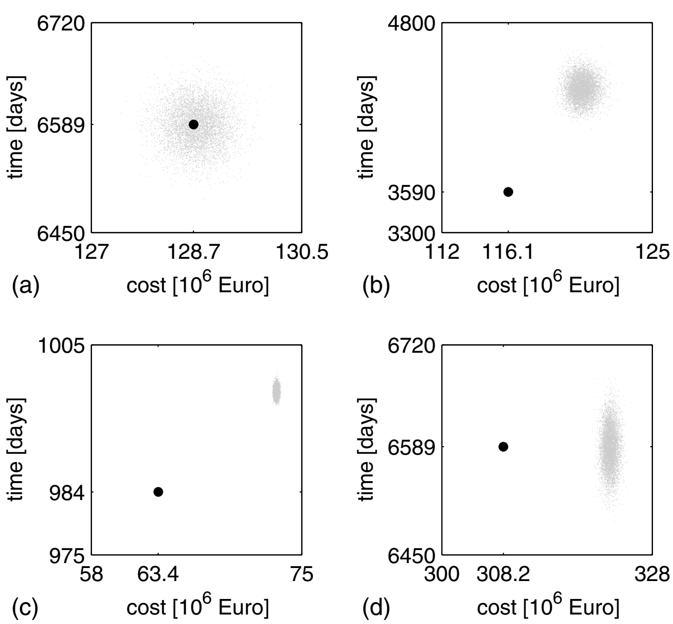

Fig. 7. Cost-duration scattergrams caused by variability; the deterministic total cost and total duration are shown with a black dot, and the cost-duration scattergrams that represent the variability are shown with a gray cloud for (a) tunnels; (b) viaducts; (c) cuts and embankments; (d) all the structures

Hence, when modeling the construction of all structures (tunnels, viaducts, cuts, and embankments) [Fig. 7(d) and Table 6], the deterministic total cost is smaller than the mean total cost because the deterministic total costs of viaducts and of cuts and embankments are smaller than the respective mean total costs. The deterministic total duration is equal to the mean total duration of tunnels, viaducts, cuts, and embankments on the critical path, where the tunnels have the longest duration. Thus, the deterministic or mean total construction duration of all structures is equal to the deterministic or mean total duration of the tunnels (all other activities take a shorter time).

From the study of the impact of variability on the total cost and total duration, a first conclusion can be drawn: the practice of calculating the deterministic total cost and total duration with the mode (most probable) input cost and duration is highly problematic: the deterministic total cost and total duration calculated with the mode input cost and duration lie below the range of possible outcomes. The deterministic total cost and total duration should be calculated with the mean input cost and duration.

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Table 6. Cost and Duration for Deterministic Case and Cases Considering the Different Uncertainties

Construction cost and duration	No uncertainty	Variability	Variability and cost correlations	Variability, cost correlations, and disruptive events
Tunnel cost (10^6 Euro)				
Deterministic	128.7	—	—	—
Mean	—	128.8	128.8	177.6
90th percentile	—	129.2	149.4	203.0
Tunnel duration (days)				
Deterministic	6,589	—	—	—
Mean	—	6,588	6,587	8,180
90th percentile	—	6,621	6,620	8,857
Viaduct cost (10^6 Euro)				
Deterministic	116.1	—	—	—
Mean	—	120.7	120.7	122.2
90th percentile	—	121.4	121.4	124.5
Viaduct duration (days)				
Deterministic	3,590	—	—	—
Mean	—	4,329	4,329	4,330
90th percentile	—	4,432	4,432	4,433
Cut and embankment cost (10^6 Euro)				
Deterministic	63.4	—	—	—
Mean	—	73.0	73.0	81.3
90th percentile	—	73.1	76.9	92.2
Cut and embankment duration (days)				
Deterministic	984	—	—	—
Mean	—	998	998	1,350
90th percentile	—	999	999	1,913
Total cost (10^6 Euro)				
Deterministic	308.2	—	—	—
Mean	—	322.4	322.5	381.0
90th percentile	—	323.2	343.6	408.4
Total duration (days)				
Deterministic	6,589	—	—	—
Mean	—	6,588	6,587	8,180
90th percentile	—	6,621	6,620	8,857

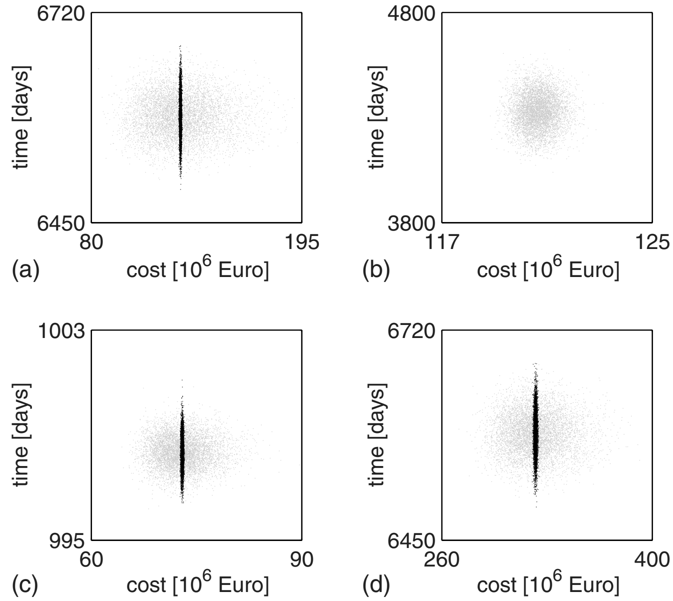

Fig. 8. Cost-duration scattergrams caused by variability (black cloud) and scattergrams for variability and cost correlations (gray cloud) for (a) tunnels; (b) viaducts; (c) cuts and embankments; (d) all the structures; due to cost correlations, the range of the total cost increases

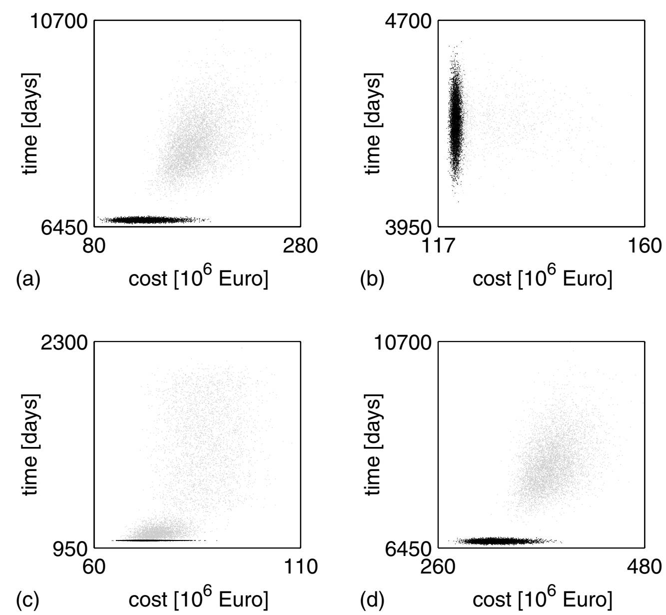

Fig. 9. Cost-duration scattergrams for all sources of uncertainty; cost-duration scattergrams caused by variability and cost correlations (black cloud) and scattergrams for variability, cost correlations, and disruptive events (gray cloud) for (a) tunnels; (b) viaducts; (c) cuts and embankments; (d) all the structures; due to the disruptive events, the ranges of total cost and total duration increase strongly; different cloud patterns are observed depending on the disruptive event

Cost Correlations

The mean total cost is the same in the simulation modeling only variability (black clouds in Fig. 8) and in the simulation modeling variability and cost correlations (gray clouds). In fact, cost correlations do not impact the mean total cost. On the other hand, the range of the total cost increases from the simulation modeling only variability to the simulation modeling variability and cost correlations, with the exception of the viaducts in Fig. 8(b) (no correlation modeled). The 90th percentiles of the total cost are larger than the mean total costs in the simulations modeling variability and cost correlations (Table 6). From these observations, the following can be inferred: First, the range of the possible total cost is underestimated if cost correlations are disregarded [this has also been discussed in Moret and Einstein (2012b)]. Second, cost correlations represent a threat (uncertainty with negative outcome) as well as an opportunity (uncertainty with positive outcome) aspect. In fact, the cost correlations cause the range of the total cost to increase on both sides of the mean (Fig. 8): there is the threat of a total cost larger than the mean total cost as well as the opportunity of a total cost smaller than the mean total cost.

Disruptive Events

Disruptive events significantly expand the range of both the total cost and the total duration. In Fig. 9(d), the gray cost-duration scattergram (variability, cost correlations, and disruptive events) is far more widely spread than the black cost-duration scattergrams (variability and cost correlations). Also the means and the 90th percentiles of the total cost and total duration increase significantly (Table 6): for instance, the 90th percentile of the total cost increases from 343.6 to 408.4 millions Euro, and the 90th percentile of the total duration increases from 6,620 to 8,857 days.

The increase in the range of total cost and total duration due to disruptive events differs in magnitude and pattern depending on the structures analyzed. For tunnels, the gray and black clouds are not superimposed, thus showing the large impact of disruptive events on cost and duration [Fig. 9(a)]. The first reason for this large impact is that in all simulation runs one or more disruptive events occur because the probabilities of occurrence of the two disruptive events are $1/800$ m and $1/500$ m, respectively, while the tunnels are several kilometers long. Second, the duration increase can be truly disruptive: in fact, the mean duration impact of one disruptive event, a cave-in, is more than 100 days (Table 5), which is three times larger than the difference of 33 days between the mean (6,587 days) and 90th percentile (6,620) of the total duration in the simulation modeling variability and cost correlations (Table 6). Third, the cost impact is also very large because it can reach 10 million Euro for the disruptive event cave-in (Table 5), which is equal to half of the 20 million Euro difference between mean (128.8 million Euro) and 90th percentile (149.4 million Euro) of the total cost in the simulation modeling variability and cost correlations (Table 6).

For viaducts [Fig. 9(b)], the black and gray clouds are superimposed for two reasons. First, disruptive events do not occur in every simulation run: the probability of occurrence is a mere 1 or 5% during the construction of a viaduct (Table 5). Second, the largest duration impact, 365 days in the case of a construction accident or problem, is less than 10% of the mean (4,329 days) total duration of the simulation modeling variability and cost correlations (Table 6). On the other hand, the cost impact of the disruptive events can be truly disruptive [Fig. 9(b)]. In fact, it can reach 30 and 50% of the total cost (Table 5).

For cuts and embankments [Fig. 9(c)], two distinct gray clouds are observed. Both are not superimposed with the black cloud, thus showing the truly disruptive nature of the events and their impact. The disruptive event of flooding determines the lower gray cloud: its impact is limited to 2% (~1.5 million Euro) and 35 days (Table 5) compared with a mean total cost of 73 million Euro and a mean total duration of approximately 1,000 days in the simulation modeling variability and cost correlations (Table 6). The disruptive event of differing site conditions determines the upper gray cloud: its duration impact can reach 100% of the total duration, while its cost impact can reach 30% of the total cost (Table 5). For all structures [Fig. 9(d)], similar patterns as for the tunnels [Fig. 9(a)] are observed for two reasons: (1) tunnels determine the construction duration of all structures because tunnels are constructed in parallel with the other structures [Fig. 6(a)] and their construction duration is the longest, and (2) the tunnels are the main cost driver in the total cost of the rail line (Table 6).

Impact of the Three Different Sources of Uncertainty

The impacts of variability, cost correlations, and disruptive events on total cost and total duration distributions vary depending on the structures (Fig. 10). The impact can be quantified by comparing the 90th percentiles of the total cost and total duration distributions with the deterministic total cost and total duration, according to the following equation:

$$\text{increase} = \frac{P_{90} - D}{D} \tag{3}$$

where P_{90} = 90th percentile of the total cost and duration distribution; and D = deterministic total cost and duration.

Clearly, modeling all sources of uncertainty causes the largest increase from the deterministic total cost and total duration to the 90th percentiles of the total cost and total duration distributions (Fig. 10). For the construction of all structures, the increase due to variability, cost correlations, and disruptive events is 30–35%. The largest increases in total cost are observed for the construction of the tunnels and the construction of the cuts and embankments: for tunnels the 90th percentile of the total cost distributions is almost 60% larger than the deterministic total cost, while for cuts and embankments it is more than 45% larger than the deterministic total

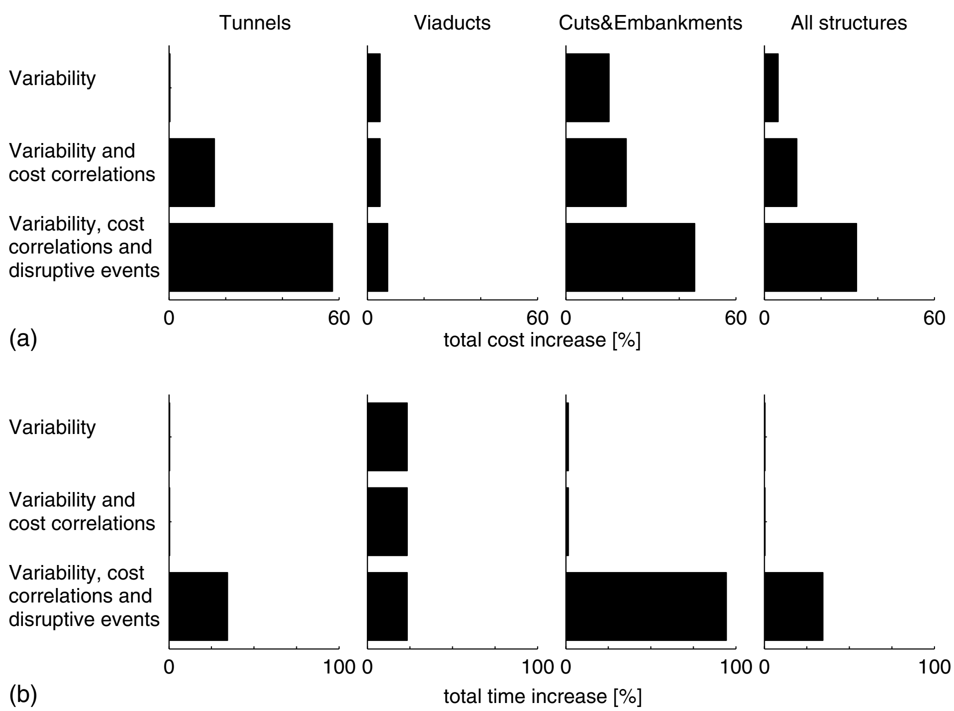

Fig. 10. Increases in (a) total cost; (b) total duration

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Table 7. Increases in Total Cost and Total Duration for Different Structures Depending on the Sources of Uncertainty

	Tunnels		Viaducts		Cuts and embankments		All structures	
Increases in total cost and duration (%)	Differential increase	Increase	Differential increase	Increase	Differential increase	Increase	Differential increase	Increase
Total cost								
Variability	0.4	0.4	4.6	4.6	15.3	15.3	4.9	4.9
Cost correlations	15.7	16.1	0	4.6	5.0	21.3	6.6	11.5
Disruptive events	41.6	57.7	3.6	7.2	24.2	45.5	21.0	32.5
Total duration								
Variability	0.5	0.5	23.5	23.5	1.5	1.5	0.5	0.5
Cost correlations	0	0.5	0	23.5	0	1.5	0	0.5
Disruptive events	33.9	34.4	0	23.5	93.9	94.4	33.9	34.4

cost. The largest increase in total duration occurs in the construction of the cuts and embankments, where the total duration increases almost 95% (Table 7).

Depending on the structure, a different impact of the source of uncertainty on total cost and total duration can be observed (Fig. 10 and Table 7):

- For tunnels, variability has an insignificant impact both on total cost and total duration, while the total cost increases due to cost correlations and disruptive events are 15.7 and 41.6%, respectively, and the total duration increase due to disruptive events is 33.9%. Thus, for tunnels disruptive events are the critical uncertainty source in the estimation of both construction cost and duration.
- For viaducts, the largest total cost (+4.6%) and total duration (+23.5%) increases are due to variability. Hence, for viaducts construction variability has the largest impact on cost and duration.
- For cuts and embankments, all three sources of uncertainty impact the total cost increase, namely variability (+15.3%), cost correlations (+5.0%), and disruptive events (+24.2%), although the disruptive events have a truly disruptive impact on the total duration increase (+93.9%). Thus, for cuts and embankments avoiding and/or minimizing the impact of disruptive events are crucial.

The different impacts of the sources of uncertainties on the total cost and total duration suggest differentiated strategies for the project stakeholders. The tunnel contractor should focus mitigation measures on cost correlations and disruptive events to contain costs and on disruptive events to meet deadlines. Mitigating the negative impact of cost correlations could be achieved by breaking the connection between activities, e.g., by stopping the work and reorganizing the work cycles. The viaduct contractor should focus on reducing the cost and duration variability in the construction process to keep both total cost and total duration within target. The earthwork (cuts and embankments) contractor must consider all three sources of uncertainty to contain the total cost but can focus on disruptive events to limit delays. From the perspective of the owner, in order to minimize the total cost of the entire infrastructure (all structures) the focus should be on disruptive events because they have the largest impact on total cost overall, while in order to minimize total duration the attention should be on the disruptive events in tunnels (in this sequence of networks [Fig. 6(a)], tunnels are on the critical path).

Parallel Construction

Throughout this paper, tunnels were constructed in sequence, viaducts were constructed in sequence, and cuts and embankments were constructed in sequence while tunnel construction, viaduct construction, and cut and embankment construction were in parallel [Fig. 6(a)]. As a consequence, the total construction duration is relatively long: depending on the sources of uncertainty, between 6,000 and 8,000 days, that is approximately 20 years. Another assumption could be that all tunnels, all viaducts, and the sequence of cuts and embankments are constructed in parallel [Fig. 6(b)]. It would follow that (1) the total costs remain the same because the total cost is the sum of all the costs, which by first approximation are equal for the construction in sequence and in parallel (discount rate and cost escalation 0%); and (2) the total duration is equal to the longest construction duration among the structures. For the specific alignment, one of the tunnels determines the longest construction duration. In this particular case, the mean construction duration would be 2,926 days (8 years) and the 90th percentile would be 3,382 days (9 years 3 months). The tunnel construction durations are very long and could be shortened by, e.g., building two parallel single-track tunnels rather than single double-track tunnels or building the tunnels from both portals. If the construction duration achieved through parallel construction of all structures [Fig. 6(b)] was considered too long, tunnels and/or viaducts and/or the sequence of cuts and embankments could be constructed starting from both ends or from multiple points in order to further reduce the construction duration. All these alternative construction possibilities can be simulated in DAT.

Discussion and Conclusions

The research presented in this paper provides an in-depth understanding of the construction process of rail lines. These are modeled as parallel sequences of four main types of structures: a sequence of tunnels, a sequence of viaducts, and a sequence of cuts and embankments. The construction process is analyzed at the activity level and considers the interconnection between activities. The proposed construction model considers the relevant aspects determining the construction cost and duration of a rail line: the construction costs are equal to the sum of the costs of the individual activities, while the construction duration is determined by the order of the performed activities on the critical path of the activity network and by the material availability in cuts and embankments construction. This integrated representation of the rail line construction with networks of activities enables one to identify and consider the uncertainties in construction cost and duration of complex projects, such as a high-speed rail line. This is crucial for the development of the uncertainty model, which analyzes the uncertainty at the activity level.

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For the first time, three sources of uncertainty (variability in the construction process, correlations between the costs of repeated activities, and disruptive events) are modeled jointly in one simulation environment: their individual impacts are quantified in Monte Carlo simulations to assess the overall impact on construction cost and time. The three sources of uncertainty are modeled jointly at the activity level: the cost and the duration of an activity are variable; the cost of the activity is correlated with the costs of other activities; and during the activity, one or more disruptive events can occur. It was found that the three sources of uncertainty produce different cost and duration impacts depending on the type of structure, suggesting structure-specific mitigation measures. Beyond the representation of uncertainty in construction, the uncertainty model has further uses: it is the starting point for mitigation measures and budget allocation, and it can be used throughout a project to update the impact of the uncertainties and to evaluate the effectiveness of countermeasures to mitigate threats.

The construction model and the uncertainty model are implemented in the simulation tool DAT. In order to model the construction of rail lines, the DAT was extended to represent the construction of not only tunnels but also viaducts, cuts, and embankments. The variability, cost correlations, and disruptive events are implemented in the DAT with probability distributions (cost and duration variability, and cost and duration impacts of disruptive events), the correlation method NORTA, and Markov processes (probability of occurrence of the disruptive events). From the perspective of practical applications, the proposed models and their implementation in the DAT represent an innovative tool to model the uncertainties in construction cost and duration of rail lines and other linear or networked infrastructure projects.

In order to validate the model and to show its practical usefulness, it was applied to a section of the Portuguese high-speed rail network RAVE. This was done using cost and time information, including their distributions, which was obtained and used by the designers of the project. As a result, the deterministic simulation exactly matches the time and cost estimate by RAVE, and the consideration of the different types of uncertainty provides important information as to which structures are most affected by the uncertainty. Specifically, the application of the construction and uncertainty models demonstrates their feasibility and effectiveness in representing the uncertainty at the activity level, in propagating this uncertainty from the individual activity to the cost and duration of the whole alignment, and in capturing the cumulative impact of all sources of uncertainty as well as the individual impact of a source of uncertainty on a type of structure (tunnels, viaducts, cuts, and embankments) and on the alignment as a whole (all structures). The cumulative impact of the analyzed sources of uncertainty causes the construction cost and duration of the modeled rail line to increase significantly beyond the deterministic: the largest increases from the deterministic estimate to the 90th percentile value are observed in the tunnel construction cost (58%) and in the earthwork (cuts and embankments) construction duration (94%). The tunnel construction cost increase is significantly larger than contingencies usually applied to transportation construction projects, and the earthwork construction duration increase almost doubles the construction duration. Although the application of the construction and uncertainty models is more time consuming than calculating a single number estimate (deterministic construction cost and duration), the insight it provides on the magnitude of the impact and the uncertainty source driving the impact is invaluable. Also, the model can be used to compare different alignments from the perspective of the impact of the sources of uncertainty.

One can conclude that construction and uncertainty models and their integrated implementation in DAT represent a major contribution to the body of knowledge in construction engineering and management. They also significantly contribute to practice by providing transportation agencies with a modeling tool to tackle cost and duration uncertainty in the construction of rail lines and other linear or networked infrastructure projects.

Limitations and Recommendations

The proposed method models in a Monte Carlo environment the uncertainty in construction cost and duration of networked systems, such as a rail line, due to three sources of uncertainty (variability, cost correlations, and disruptive events) at the level of the single activity. Through future work the proposed model could be extended to consider other sources of uncertainties, e.g., correlations between the duration of activities.

The application of the model to the case presented in this paper can so far not be compared with the completed project because the construction of the high-speed rail line has been delayed following the financial and economic crises. The deterministic simulation results were validated with the project's engineer estimates. The presented simulation results need to be compared with the metrics of the constructed project when these become available. However, realism is brought into this validation by the input from experts in the uncertainty model, specifically in assessing the probability of occurrence and the impacts of disruptive events (see "Uncertainty Model").

The presented method can model uncertainty in cost and duration due to variability, cost correlation, and disruptive events. The magnitude of the impact of these uncertainties depends on the type of structure (as shown), but clearly also on the project or the modeled alignment. Moret (2011) modeled four alignments of the Portuguese high-speed rail line and found different percentage increases in cost and duration. However, these increases, albeit not identical, confirm the need of modeling and capturing the impact on cost and duration of multiple sources of uncertainty.

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