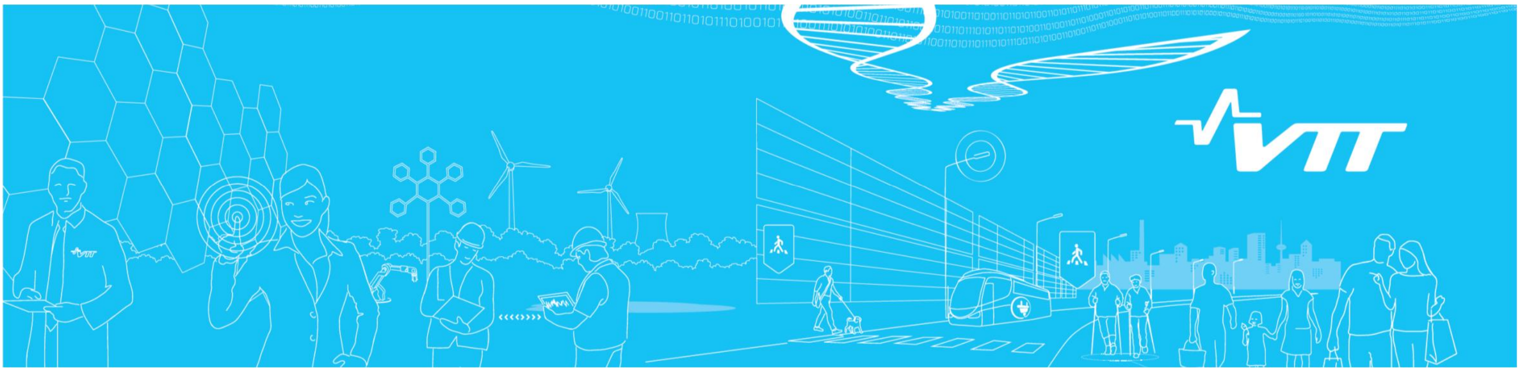

RESEARCH REPORT

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Applying importance measures in resource-constrained operation schedule risk analysis

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Summary

Emergency operations are fast response operations for preventing adverse events from harming a system, for responding to and mitigating their consequences, and for recovering from them. This report concerns schedule risks associated with them. The topic is examined in a resource-constrained setting, where replacements for broken or otherwise failed resources are not necessarily available within the operation's time frame.

In probabilistic risk analysis and reliability engineering, reliability importance measures give the sensitivity of risk to component failures or other events. Schedule risks can be defined as the delay of the completion of the operation or some specified part of it. The probability of this may be regarded as the failure probability of the operation, which enables the application of importance measures in this context. We show how to interpret importance measure concepts in this context, define various kinds of events that may cause delay in operation completion, and show how to estimate importance measures from simulated, experimental or observational data.

The importance measures are applied to an operation of clearing roads leading to a nuclear power plant from fallen trees after a storm. A stochastic activity network model developed earlier is used and improved, estimation of the most important PRA importance measures from simulation data is implemented, and estimation results are presented.

Importance measures have many applications in the risk management of emergency operations, such as resource allocation.

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1. Introduction

Prevention and emergency (P&E) operations are fast response operations for preventing adverse events from disturbing a system's operations or damaging its equipment or structures, for responding to and mitigating the consequences of adverse events, and for recovering from such events (Karanta, 2014). They are operations that involve more than one actor, more than one task to be completed, precedence relations between tasks, usually limited resources and a finite amount of time for completion; thus, they may be modelled as projects, which has several advantages: foremost, the scientific results of decades of project management research are available to bear on the analysis. In (Karanta 2014), activity networks were used as the representation formalism for P&E operations, and a small case study – blocking oil from entering the cooling water system of Fortum's Loviisa nuclear power plant – was presented.

P&E operations occur in a wide variety of risk management applications. Within nuclear safety, the main goals of prevention and emergency operations are to prevent production breaks and damage to utility, minimize damage, protect personnel and prevent a release of radioactive substances. Some examples of such operations are recovery from a loss of coolant accident (LOCA), evacuation of personnel, and fire extinguishing.

This report deals with schedule risks of a P&E operation (other risks associated with P&E operations are cost risks, end product quality risks, and safety risks). These are considered in a situation where available resources are scarce; in the present context this means that an unavailable resource, e.g. a fire truck, cannot immediately be replaced by a similar resource.

The approach used in this report is to define importance measures for different variables. The idea behind this approach is that when resources are scarce, the most critical resources, activities and events (hazards) should be identified so that they can be taken into account in planning. For example, more resources might be allocated to the most critical activities, more reliable equipment might be purchased to be used as critical resources etc.

The case considered is clearing of fallen trees from roads leading to Hästholmen nuclear power plant site after a storm. The case was modelled and analysed in (Karanta 2015), and risk estimates were obtained. The model and its computer implementation of that report will be used in the present report. Importance measures will be defined for the case, with a view of generalizability to a more general emergency operations setting.

2. Importance measures for schedule risk analysis

Importance measures (Kuo and Zhu 2012, van den Borst and Schoonakker 2001) are measures of sensitivity of a system's performance to events such as failure of a component. In systems reliability theory and probabilistic risk analysis (PRA), the system's performance is usually defined as its reliability, and thus importance measures in PRA represent the impact of an event on system reliability. Importance measures have many important applications in risk management, such as optimization of plant design by adding or removing components or systems, optimization of plant performance by changing the test and maintenance strategy, and determining the effect of taking a component out of service (van den Borst and Schoonakker 2001). However, they have wider applicability in e.g. fault diagnosis, mathematical programming, and network design (Zhu and Kuo 2014).

Importance measures quantify the impact of a variable obtaining (a) specific value(s) to the system risk. In probability theory, the case of a variable obtaining specific values is called an event. The impact is measured as the system risk (system failure probability) on the condition that the event has occurred or does not occur.

Importance measures are usually categorized into three classes (Birnbaum 1968) according to the knowledge needed in determining them:

- *Structure importance measures* measure the relative importance of components with respect to their position in the system, without referring to their reliability. They can be determined from the structure function of the system.

- *Reliability importance measures* are evaluated at a fixed time point. They depend on both the structure function and on the reliabilities of the individual components. This category of measures is the most important from the PRA point of view, and measures belonging to this category are usually standard output of PRA codes.

- *Lifetime importance measures* are used when the system and its components have long-term or infinite service missions. They depend on positions of components in the system, and component lifetime distributions. They can be time-dependent (give the importances of components in the system's lifetime including the debugging period, normal life or operational period, and wearout period), or time-independent (give a summary measure of a component's importance over a longer time period, e.g. the system lifecycle).

In the analysis of a single emergency operation, we consider only reliability importance measures. This choice is motivated by two considerations. First is the fact that an emergency operation is normally completed in a very limited timeframe (from minutes to a few days), and therefore lifetime importance measures have little significance in their analysis. Second is the fact that many events in an emergency operation affect several nodes in the activity network (see section 2.3), and therefore the position of a single node in the activity network is not necessarily a meaningful indicator of an event's importance.

2.1 Schedule risks and events

Schedule risk is the risk that an operation (or some specified part of it) will not be completed in time. It can be defined as the probability that the time from operation start to operation completion, T_E, takes longer than a specified time T:

$$R = P(T_E > T) \quad (1.)$$

For the purposes of this report, we define the following three event modalities. These are analogous to the definitions by (van den Borst and Schoonakker 2001) in the context of PSA importance measures. Denote the j^{th} event by X_j, and its probability by p_j.

- $X_j = true$: the event is assumed to have occurred. For example, it is known that a truck has broken.
- $base$: no assumptions about the occurrence of the events are made; they are assumed to occur with the probabilities associated with them. In this case, the system failure risk is the unconditional risk (which is, for schedule risk, defined in equation 1.).
- $X_j = false$: the event is assumed not to have occurred.

The most widely used importance measures can be defined in terms of system failure risk conditioned on these modalities. For schedule risk, these conditional probabilities are

$$R(X_j = true) = P(T_E > T|X_j = true), \tag{2.}$$

$$R(base) = P(T_E > T), \tag{3.}$$

$$R(X_j = false) = P(T_E > T|X_j = false). \tag{4.}$$

In the context of schedule risks, we need a way to map these modalities to activity durations. Define probability density function for the duration of activity i as follows.

For the modality that the event has occurred, let the density function be

$$f_{i,X_j=true}(t) \tag{5.}$$

For the modality that no assumptions about the occurrence are made, let the density function be

$$f_{i,base}(t) = p_j f_{i,X_j=true}(t) + (1 - p_j) f_{i,X_j=false}(t) \tag{6.}$$

For the modality that the event is assumed not to have occurred, the density function is

$$f_{i,X_j=false}(t) \tag{7.}$$

It is to be noted that in the base case, the probability density function is a mixed distribution (McLachlan and Peel 2000).

2.2 Some prominent importance measures

Numerous importance measures have been defined for different purposes. In this section, the importance measures that were found to be the most used in an international survey (Vasseur and Lory 1999) are listed. We use the representation of the importance measures used in (van der Borst and Schoonakker 2001), but the reader is reminded that other ways of representing these importance measures exist (see e.g. Kuo and Zhu 2012).

Risk reduction worth RRW is defined as

$$RRW = \frac{R(base)}{R(false)} \quad (8.)$$

Risk achievement worth RAW is defined as

$$RAW = \frac{R(true)}{R(base)} \quad (9.)$$

Fussell-Vesely factor FV

$$FW = \frac{R(base) - R(false)}{R(base)} \quad (10.)$$

Birnbaum importance BI

$$BI = R(true) - R(false) \quad (11.)$$

In (van der Borst and Schoonakker 20001), other importance measures (risk reduction, criticality importance, risk achievement and partial derivative) were represented in a similar manner.

2.3 Importance measures for schedule risks

In defining importance measures for schedule risks in an emergency operation, there are two things to consider:

- identify what kinds of events may affect the completion time of the operation.
- Consider how to model and analyse those events in the emergency operations context.

In the following, we go through some central kinds of events that might affect the completion time of an emergency operation.

2.3.1 Loss of a resource during the operation

In principle, any resource that is used in an emergency operation might be lost. For example, a fireman might be injured, or a fire truck might be damaged in one way or another during the operation. This affects the duration of the activity where the resource was used at the time of its loss (if any), and all subsequent activities where the resource was planned to be used. The effect of resource loss depends on context. If spare resources are available, they might be called in to replace the lost resource. Some resources (e.g. a broken fire truck) might be repaired, if feasible. Remaining resources might be re-allocated, if the lost resource was allocated to high-importance activities. In resource-constrained operations, spare resources are not necessarily available, and in emergency operations, there might not be time for repair. In any case, the loss of a resource causes time delay in the duration of activities that it affects.

The effect of resource loss on schedule risk may be accounted for in the following way.

1. Identify which resources might be lost and for what reasons. Assess the probability that a resource is lost in an activity, for all relevant activities (for example, by constructing a PRA model for the loss of the resource). Identify also all the activities that are affected by resource loss (activities that use the resource lost).

2. Specify probability distributions for the time for the completion of the present activity, and all subsequent activities that use the lost resource, conditional on that the resource is lost. For example, if the resource is repaired before continuing with the present activity, a suitable distribution might be the sum of the activity's duration distribution and resource repair time distribution.

3. Use the probability distributions of activity completion under normal circumstances (i.e. without loss of the resource), and the distributions specified in item 2 to formulate completion time probability distributions (5.)-(7.) for the affected activities.

4. Analyze the operation model augmented with these probability distributions as explained in section 2.4.

2.3.2 Performance decline

There are situations where resources cannot be used to maximal utility; call those situations adversary events. An example of an adversary event is bad weather, which might cause that a fire truck cannot be driven at full speed. Using the resource at a lower performance level than it is capable of results in delay in activities where the resource is used.

Performance decline of a resource can be modelled and taken into account in analysis in the following way:

1. Identify what parameter(s) describe the performance of the resource. For example, the performance of a fire truck may be described by its maximum speed (e.g. 100 km/h). Denote this parameter by α, and the parameter value at normal performance by α_{normal}. Assess the probability $p_{decline}$ that the performance parameter is declined (e.g. the probability that weather is such that the fire truck cannot drive at full speed).

2. Represent the duration of the activities where the resource is used in terms of the parameter(s). For example, the time it takes for a fire truck (including its crew) to move from one segment with fallen trees to another can be described as the time needed to accelerate the truck to maximum speed, the time spent driving at maximum speed, and the time to decelerate the truck when the next segment is encountered.

3. Assess the effect of the adversary event to the performance. For example, in bad weather the maximum speed of the fire truck might be 60 km/h instead of 100 km/h. Denote this lowered performance parameter by $\alpha_{declined}$

4. Augment the operation schedule risk model with the following model: $\alpha = \alpha_{normal}$ with probability $1 - p_{decline}$, and $\alpha = \alpha_{declined}$ with probability $p_{decline}$. Proceed in the manner explained in section 2.4.

2.3.3 Other types of events

There are also other types of events that cause schedule risks in operations. Some of these are shortly described in this section, because they were not implemented in the computation.

Some events may not necessarily cause a resource to fail, but rather increase resource or activity failure probability. This may happen, for example, when a piece of equipment must be used continuously for a long time, or beyond its maximal recommended capacity. The increase in failure probability may be treated as decline in a performance parameter, and handled as explained in section 2.3.2.

Some events may cause performance decline and failures in many activities that might not necessarily share anything else, such as shared resources or precedence relations, between them. Examples of such events are bad weather (see section 2.3.2), darkness, and flood. The key in modelling the effect of such events is to identify all the activities and parameters that they affect ; then one can proceed in the manner explained in section 2.3.1.

Random variation in activity completion also causes schedule risk, and it is evident that some activities cause more schedule risk than others due to their randomness properties and position in the activity network. The duration of an activity varies due to random reasons, even without failure of equipment, decline in performance etc. If the activity happens to be in the critical path of the activity network, such a random delay causes delay in operation completion, which in turn might lead to exceeding the operation time limit. If the activity is not in the critical path of the activity network, some path through the activity might become critical if the duration of the activity is sufficiently large.

To apply the most common importance measures, we need to define a failure event for an activity duration. A suitable candidate for this is that the activity takes longer than expected, i.e. the failure event is $T_i > ET_i$. Using this definition, assessment of the importance of the activity may now proceed as explained in section 2.4. Intuitively, two properties of an event should render it more significant than other events: first, that the corresponding activity is on the critical path, and second, that the probability distribution of the activity's duration is heavy-tailed (intuitively speaking, much of its probability mass is on high values relative to expectation).

2.4 Importance measures from empirical/simulation data

Next we operationalize the importance measures so that their values can be estimated from simulation/empirical data.

The basic scheme in the computational implementation is that for each activity in the activity network, a probability distribution for its duration is specified, and the network is simulated by assigning each activity a random value from its duration distribution. Thus, we need to specify two things: first, which probability distributions for the durations of the activities to use under different modalities for the events, and second, how to evaluate the conditional risks of equations (2.)-(4.) from the simulation results (basically, a list of operation completion times, one for each simulation round).

The first thing is to specify how event modalities are represented in a simulation model of an activity network. This happens simply by using probability density (5.) when simulating operation completion times under the $X_j = true$ modality, probability density (6.) when simulating under the $base$ modality, and probability density (7.) when simulating under the $X_j = false$ modality. In practice, all these densities are special cases of probability density (6.): probability density under the $X_j = true$ modality equals the density obtained from (6.) by setting $p = 1$, and probability density under the $X_j = false$ modality equals the density obtained from (6.) by setting $p = 0$; from the implementation point of view this is convenient, because only the mixture distribution needs to be implemented (the other modalities can be handled by setting $p = 1$ or $p = 0$).

The second thing to specify is how to evaluate the conditional risks of equations (2.)-(4.). This may be accomplished by simulating the operation under the event modalities needed in calculating the importance measure, and then counting the proportion of project completion times that exceed the given time limit from all project completion times in that simulation round.

Denote the number of simulation rounds that return an operation completion time exceeding the specified limit (i.e. the operation has failed on that simulation round) when $X_j = true$ by $N_{fail}(X_j = true)$, the number of simulation rounds that return an operation completion time exceeding the specified limit when simulating under the $base$ modality by $N_{fail}(base)$, and the number of simulation rounds that return an operation completion time exceeding the specified when $X_j = false$ by $N_{fail}(X_j = false)$. Further denote total number of simulation rounds by $N(X_j = true)$, $N(base)$ and $N(X_j = false)$, respectively. Then the numerical risk estimates of (2.)-(4.) are simply

$$\hat{R}(X_j = true) = \frac{N_{fail}(X_j = true)}{N(X_j = true)}, \quad (12.)$$

$$\hat{R}(base) = \frac{N_{fail}(base)}{N(base)}, \quad (13.)$$

and

$$\hat{R}(X_j = false) = \frac{N_{fail}(X_j = false)}{N(X_j = false)}. \quad (14.)$$

These risk estimates can then be assigned in the importance measures presented in section 2.2 to obtain numerical estimates for the importance measures.

2.5 Use of importance measures in emergency operations risk management

There are several ways in which importance measures can be utilized in the planning (and maybe even execution) of emergency operations. These are roughly analogous to their use in the PRA of nuclear power plants.

If a particular resource, for example a fire truck, is found to have high importance to operation success (in terms of meeting its deadline), redundancy in the form of reserve fire trucks in the emergency department might be called for. This might lead to changes in the allocation of fire trucks to fire stations in the emergency department (in the case of IUPL, for example from Myrskylä fire station to Loviisa fire station).

In the resource-constrained setting, it can be analysed what is the effect of the unavailability of certain resources (in our example case, firemen, chainsaws etc.) on operation schedule risk. The results of this can be used in allocating resources to the operation. Also when considering investments in equipment, importance measures help decide which equipment need to be high-quality and reliable (and therefore more expensive), and which equipment do not need to be so.

The analysis of the contribution of different activities to the schedule risk helps in concentrating process improvement efforts to critical activities. For example, if it turns out that moving cut trunks and branches to the roadside has high risk importance concerning schedule, efforts may be put in organizing this activity in a more efficient manner, in considering more expedient equipment for the purpose, and in training that part of the operation more.

3. Implementation

The model and its analysis were implemented in Microsoft Excel 2010, using the Visual Basic for Applications (VBA) programming language native to Excel. The Monte Carlo simulation, implemented with Excel Solver of Frontline Systems in the previous year, was now implemented directly in VBA. This caused programming work (e.g. the implementation of generating random numbers from various probability distributions), but contributed towards creating a standalone schedule risk analysis program.

As an example of code implemented for the estimation of importance measures, the function used for simulating a mixture distribution (6.) in the case of the failure of a fire truck (see section 5.1) is shown in Figure 1. As can be seen, its implementation is simple and straightforward.

```
Function mixed_distribution_for_time_in_segment(n As Integer, length As Double, p As Double)
    Dim k As Integer
    Dim repair_ave, repair_std As Double
    repair_ave = Range("average_time_of_truck_repair")
    repair_std = Range("standard_deviation_of_truck_repair")
    k = rand_bernoulli(p)
    If k = 0 Then
        mixed_distribution_for_time_in_segment = time_spent_in_segment(n, length)
    ElseIf k = 1 Then
        mixed_distribution_for_time_in_segment = time_spent_in_segment(n, length) _
                                                + rand_lognormal(repair_ave, repair_std)
    Else
        MsgBox ("something wrong with rand_bernoulli")
    End If
End Function
```

Figure 1. The function for simulating a mixed distribution for the delay caused by truck failure.

4. Description of the road clearance case

To illustrate the concepts and methods introduced in chapter 2, we consider the case of clearing roads leading to the Hästholmen nuclear power plant site from fallen trees after a west storm. The case has been described in (Karanta 2015). Although there are sufficient materials and spare parts to run the plants for several weeks without external supplies, there is a schedule risk associated with not clearing the roads in time: in an exceptional situation (such as after a heavy storm) there might be a need to enable trained personnel and experts to enter the site to better manage the situation. Such people include operators (to free or complement the operators already on site), subsystem (e.g. electricity subsystem) experts, and probabilistic risk analysis experts to analyse the risk significance of various actions. The nominal time limit for considering the clearance of roads (and thus enabling the experts to come to the site) a success is four hours.

The basic setting of the clearing process is as follows. After a storm, it is noted in the NPP site that trees have fallen on the roads leading to the site, preventing traffic on those roads. Due to the exceptional situation, the fire squad of the site has to stay in the plant area in case it is needed there. Therefore, help in clearing the roads is requested from the Loviisa fire station of the Eastern Uusimaa Emergency Services Department (IUPL). A crew of four firemen takes the mission in a fire truck equipped with clearing equipment (chainsaws, winch etc.).

In a previous report (Karanta 2015), this clearing of roads was modelled and analysed by partitioning the relevant roads to segments based on whether there were trees on the roadside that could fall and block the road. An activity network model for a unit (firetruck and 4 crew members) moving from segment to segment, and clearing the trees from each segment, was constructed. The main road considered was Atomitie; also the case that the crew foreman of the truck clearing Atomitie would call in another unit to clear Lappomjärventie was considered. Probability distributions were associated with each work phase within an activity (e.g. cutting a tree trunk, driving from one segment to the next). The model was solved by Monte Carlo simulation. The simulation model was implemented in Microsoft Excel, utilizing the Excel Solver simulation add-in.

In the last year, the activity network model and its computer implementation have been modified in some respects. The first improvement concerns the handling of the situation where the fire truck foreman calls in another crew to clear Lappomjärventie after arriving on scene in Atomitie. In the previous model, only the cases that the foreman didn't call for help at all, or that he called for help in any case after arriving at the scene, were considered. In the improved model, the fireman calls for an extra firetruck if the number of fallen trees in a segment exceeds a certain number (e.g. 30 % of the total inventory of trees in that segment). This approach is more realistic in the sense that the foreman does not call for help unless there is a considerable risk that the schedule limit is not met. A second improvement concerns simulation itself, which has been implemented in Visual Basic for Applications (VBA) code; this removes the need to use an external add-in in simulation and gives better control over various aspects of simulation.

5. Example events in the road clearance case

To illustrate the concepts and methods introduced in section 2, we consider examples of how they might be applied in the road clearance case described in section 4. The numerical figures used are not based on any real data or expert judgment, but are chosen here for illustration purposes only.

5.1 Failure of a fire truck during an activity

The first case is failure of fire truck during the clearing of a road segment from trees. We assume that the crew is able to repair the truck, but the repair takes some time. The total working time spent in the activity is then the sum of the time spent clearing (cutting a tree fallen on the road, moving the branches and tree trunk parts to roadside, and moving to the next fallen tree) and the time spent repairing the fire truck.

We assume that the probability of this event is 0.1. We assume that truck repair time is lognormally distributed, with average of 15 minutes and standard deviation of 5 minutes. To reduce computation times, we assume that truck failure can only occur in one road segment, that of Atomitie 454-483. Further, we set the operation failure threshold - the time limit that operation completion must not exceed – to two hours. As stated in section 4, the time limit for the operation is actually 4 hours, but the probability of the operation exceeding 4 hours is so small (see Karanta 2015) that to avoid an excessive number of simulation rounds the smaller time limit was chosen.

5.2 Lowered maximum speed of fire truck due to bad weather

The second case is that, due to bad weather conditions (slippery roads), the fire truck cannot move faster than 70 km/h (the top speed is assumed to be 90 km/h ordinarily). Further, we assume that the probability of such weather conditions is 0.2.

6. Results

The truck failure event of section 5.1 was simulated 1000 times for each modality. The operation completion time exceeded the threshold as follows: $N_{fail}(true)$ = 484,

$N_{fail}(base)$ = 245 and $N_{fail}(false)$ = 200. Thus, the importance measure estimates presented in Table 1 are obtained.

Table 1. Importance measures for the truck failure event.

Importance measure	Value
Risk reduction worth	RRW=$\frac{245}{200}$ = 1.225
Risk achievement worth	RAW=$\frac{484}{245} \approx$ 1.9755
Fussell-Vesely	FW=$\frac{245-200}{245} \approx$ 0.1836
Birnbaum importance	BI=$\frac{484}{1000} - \frac{200}{1000}$ = 0.284

The lowered maximum speed case of section 5.2 was also simulated 1000 times. In this case, the operation completion time exceeded the threshold as follows: $N_{fail}(true)$ = 251, $N_{fail}(base)$ = 209 and $N_{fail}(false)$ = 193. Thus, the importance measure estimates presented in Table 2 are obtained.

Table 2. Importance measures for the lowered maximum speed of fire truck event.

Importance measure	Value
Risk reduction worth	RRW=$\frac{209}{193} \approx$ 1.0829
Risk achievement worth	RAW=$\frac{251}{209} \approx$ 1.2010
Fussell-Vesely	FW=$\frac{209-193}{209} \approx$ 0.0765
Birnbaum importance	BI=$\frac{251}{1000} - \frac{193}{1000}$ = 0.058

As can be seen, with these values the reduction of maximum fire truck speed is not as important as truck failure. A lesson that might be drawn from this is as follows: it is better that the fire truck driver does not drive at maximal speed in bad weather. Even though that nominally might save time, it leads to increased probability of accident or truck failure, and thus is worse from schedule risk point of view than driving at moderate speed. However, this lesson applies only with the invented parameter values of section 5, and drawing conclusions in the real-life case would presuppose that parameter values with a firmer basis would have been obtained somehow.

7. Utilizing resource-constrained project scheduling models and methods

An alternative to deal with schedule risks in the resource-constrained setting was also considered, that of utilizing resource-constrained project scheduling models and methods (Artigues et al 2008; Neumann et al. 2003; Hartmann and Briskorn 2010). It would have been used so that an optimal resource allocation would have been formed for each significant scenario (e.g. loss of a fire truck), and schedule risks would have been analysed for the schedules thus generated. However, the approach was deemed to be unsuitable for risk analysis purposes, because it is normative (an optimal schedule is sought). Risk analysis of P&E operations should be based on what is likely to happen rather than what should happen.

8. Conclusions

A method for calculating risk importance measures for schedule risk of a prevention and emergency operation has been introduced. The method is based on identifying events and other factors that affect schedule risk, and then applying ordinary PRA importance measures (with event modalities defined suitably). The method has been operationalized through specifying how events and other factors can be presented in a simulation model, how event modalities can be taken into account in simulation, and how schedule risks conditioned on different modalities can be estimated from simulation (or experimental) data. To the present author's knowledge, neither calculating importance measures for schedule risks, nor estimating importance measures from simulation data have been addressed in the scientific literature.

The developed methods are illustrated by applying them in a case of clearing roads leading to the Hästholmen NPP site from fallen trees after a storm. The implementation of importance measure calculations proved to be rather easy and straightforward.

Importance measures can be utilized in many ways in the management of schedule risks of emergency operations.

Some important research directions in the schedule risk analysis of emergency operations include the specification and application of group importance measures, assessment of the applicability of structural and network importance measures, and the consideration of uncertainty importance measures in this context.

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