A method to determine the total risk exposure in large infrastructure projects

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ABSTRACT: This paper discusses the problem of finding a formal method to measure the total risk exposure in large infrastructural projects. A methodology is proposed to find weight factors for different types of consequences so they can be converted to a common measure and summed. This is done using the Analytic Hierarchy Process. One team of experts that make the pair-wise comparisons comes from the Hallandsås railway tunnel project, presently under construction. Another team comes from the Citybanan railway tunnel project in Stockholm, which is still in the planning and design stage. A principle to describe and take into account the effect on the total risk exposure, when one or more risks realise, is also proposed (this effect is time dependent).

1 INTRODUCTION

1.1 *Background*

When doing risk management for a project, the decision to accept the risk, mitigate it or analyse it further is usually done for each identified risk separately. Also, the decision rules (often shown as colours in a risk matrix) are commonly decided on for a single risk. In a large infrastructural project, there will be many identified risks and possibly many risks individually accepted. This can mean that there is a total risk exposure that exceeds what can be accepted and that risks that have been accepted must be revised. Usually, the total risk exposure is defined as the sum of the expected losses. This, however, does not take into account that the risk is often compounded by several consequence categories (e.g. time and cost overdraft, health and safety damage, environmental damage, loss of goodwill). These categories cannot just be added, as they are measured in quite different units. A common measure (like utilities) for all the categories is therefore to be desired.

It must also be recognized, that if a risk is realised, this will have a bearing on how other risks are assessed. Often, the consequences of a risk belonging to a category like goodwill are assessed to be higher immediately after another risk has been realised. (Two risks that occur close in time will hurt the project more than if they occur with a long time between them). This means that the total risk exposure depends not only on the calculated expected losses but also on the history of realised risks.

During active risk management work within the Hallandsås Project, a large infrastructure project in Sweden, the above shortcomings triggered an investigation into the problem of total risk exposure. This resulted in a research programme (preliminary study) financed by SBUF (Development Fund of the Swedish Construction Industry). The findings from this preliminary study are presented herein.

1.2 *The Hallandsås project*

The Hallandsås Railway Tunnel Project is a major infrastructural project presently under construction in southern Sweden. The Hallandsås project is part of a large investment aiming at expanding and rebuilding the west coast railway line between Gothenburg and Malmö. Two parallel 8.6 km long tunnels are being excavated, by means of a 10.6 m diameter hard rock mixed shield tunnel boring machine (TBM). The project started in 1991 but due to technical and contractual problems related to the use of an open tunnel boring machine and a chemical grout causing environmental damage two attempts to complete the tunnels have failed.

The project started for the third time in 2003 using a much more advanced technique including the shielded TBM and a continuous segmental lining to control water ingress. The client is the Swedish Rail Road Administration (Banverket) and the contractor a joint venture between Swedish company Skanska Sverige AB and French company Vinci Construction

Grand Projets (Skanska-Vinci HB). The contract is a design and built contract amounting to almost 400 M€ and completion is expected during 2012.

The project is considered to have a high risk profile and three significant circumstances particular to the project are:

- The history, including two previous failures and a public debate on the legitimacy of the project.
- The very complex geological and hydro geological situation.
- The high environmental demands, including comprehensive chemical evaluation of all chemicals used within the project and tight restrictions on water ingress.

As a result of this, the client and contractor jointly decided to implement an advanced risk management system and to work in a pro-active manner to meet all project risks

A special risk advisory group (RAG) was instigated with the purpose of independently reviewing the project risk management work and to support the project organisation in handling risks.

A risk database provides the hub in the risk management work and all risks are administrated through this database. The database will provide the status of all identified risks.

In the data base a risk matrix is the major means for making decisions about the risk under study.

The matrix which was designed for the Hallandsås project is shown in Figure 1.

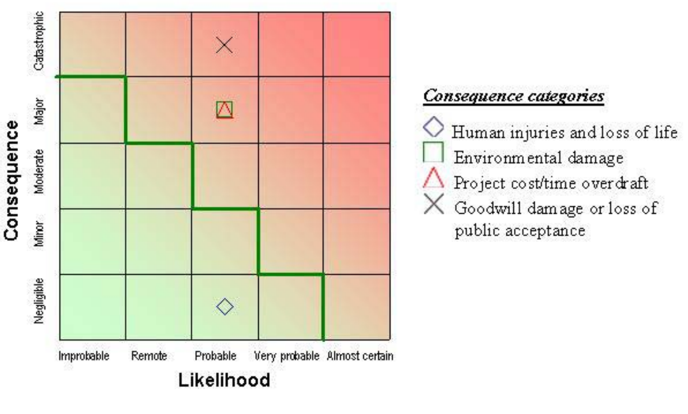

Figure 1. Risk matrix used at the Hallandsås project.

As can be seen from the figure, the matrix has five likelihood classes and 5 consequence classes. The consequences are divided into four categories:

- Human injuries and loss of life
- Environmental damage
- Project cost/time overdraft
- Goodwill damage or loss of public acceptance

That Environmental damage and Goodwill damage are shown separately is too a large part due to the previous history of the project, with environmental damage and local public outrage. This has made the owner very sensitive to further damage in those categories. In Figure 1 a bold guideline is shown in the matrix, this line is intended to help the decision maker in deciding between the three possible actions for the risk:

- Accept it as is
- Accept it after mitigation
- Make a detailed analysis of the risk and then take the decision

The decision is made subjectively, especially for the last alternative, where the risk plots close to the guideline. These decisions are made for each risk separately, without regard for other risks in the system. This is a common practice but it has the major drawback that the implicit and sometimes erroneous assumption is made, that if all risks are individually acceptable, then the system safety is acceptable, see e.g. Clemens et al. (2005).

After using the risk management system for some time, the project managers requested a measure of the total risk exposure within the project. The risk data base provides a good picture of individual risks but the total risk picture is not regarded.

2 TOTAL RISK EXPOSURE

The total risk exposure of a project can be visualised in several ways. One method which has been used by some of the authors in another project is simply to note the number of risks (of the different categories) in each cell of the matrix, see Figure 2.

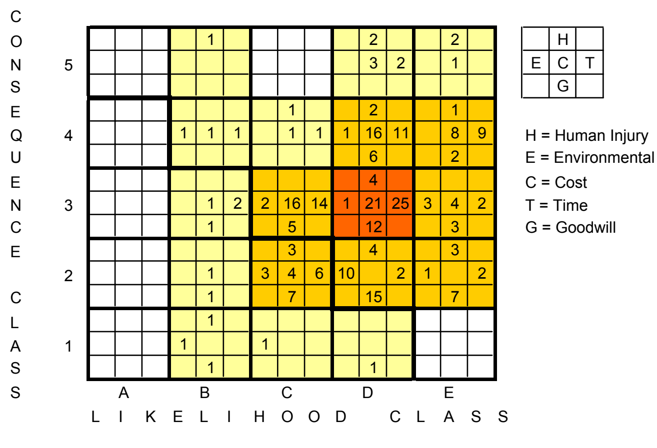

Figure 2. Total risk exposure shown by number of risks in each cell.

If you want to show the total risk exposure as a diagram, you will either have to use a 3D-diagram or you will have to divide it according to e.g. consequence class.

Neither of these methods of visualising the total risk exposure is quite adequate as a decision support when it comes to decisions about the total risk.

The decision problem for the system has two parts:

1. The fact that all risks are individually accepted does not mean that the system risk is acceptable. This in turn might call for a revision of risks already accepted and/or new decision criteria for new risks to be managed.
2. Mitigations should be applied when the cost for the mitigations is lower than the expected cost for the risk. Are mitigations worthwhile?

None of the visualisations shown are really helpful when it comes to handling these two problems as one has to look at each damage category separately. Even if one might compare each category against a risk budget for that specific category, some sort of a single measure is preferred.

If one has just one consequence category, say cost overdraft, the problem is solvable by just adding the expected cost of all risks. (We prefer to use the definition of risk as the triplet {scenario; probability; consequence}, see Kaplan & Garrick (1981) and use the decision theory term "expected loss" for the product probability $*$ consequence, see Equation 1.

$$TR(A) = \sum_{i=1}^{i-n} P(Risk_i) \cdot C(Risk_i) \qquad (1)$$

Where TR (A) is the total risk exposure for category A consequences. This summing has some prerequisites:

- The consequences can be measured using a scale (interval or ratio)
- The risks are statistically independent
- All risks in the sum are active during the time period under study
- Repetitive risks are assessed correctly

In the case that there are several consequence categories, one needs to convert them into some common measure, i.e. there is need for a set of conversion factors for the different categories.

There is also a need for the description of each consequence class to be such that you have a (more or les) constant ratio between the cells, see e.g. Clemens et al (2005). There is a corresponding demand on the likelihood classes.

3 CALIBRATION OF RISK MATRIX AXES

3.1 *Likelihood*

The likelihood axis is the easiest to calibrate, as it is already numerical. A discussion about suitable steps etc. can be found in Clemens et al. (2005) and examples of such calibrations can be found e.g. in MIL-STD 882E.

3.2 *Consequences*

The consequences can roughly be divided into two basic types; those that amount to a purely monetary loss and those that amount to a breach of moral and/or ethical values. It should be noted that nearly all consequences have a monetary part, but that for some of them the impact on the project caused by the non-monetary part is by far the heavier.

For some of the consequence categories the damage severity is only described verbally and it is therefore necessary to find a wording that is not ambiguous. In order to check the wording it is necessary to compare the different consequence classes in a stringent way where one can have some figure which describes the severity. Using such figures, it is also possible to use them as conversion factors (CCF) making it possible to calculate the total risk exposure as a single number, see Equation 2.

$$\text{TRE} = \sum_{i=1}^{i=n} P(Risk_i) \cdot \sum_{\substack{Consequence \\ categories}} C(Risk_i) \bullet (CCF) \qquad (2)$$

Where TRE is the total risk exposure. This total risk exposure is of course expressed in a subjective unit akin to the "utilities" used in decision theory.

One way to make this comparison between the different categories and different consequence classes is the Analytic Hierarchy Process, see e.g. Saaty (1990) and the ExpertChoice homepage. The AHP methodology comprises the following main steps:

- Structuring of the problem in a hierarchic ordering (tree structure)
- Pair-wise comparisons at each level in the structure
- Evaluation

4 TESTING AHP METHODOLOGY AT THE HALLANDSÅS PROJECT

4.1 *AHP Procedure*

The first test of the suitability of the AHP was made at the Hallandsås Project. When making the structure it was decided not to include the category "Human injuries". It was felt that including it and consequently making the comparison between human lives and money would cause criticism. The hierarchy used is shown in Figure 3.

The hierarchy used is rather simple with the top event being the "Least desirable consequence", at the next level the different consequence categories and under these the respective consequence classes.

The persons doing the comparisons were picked from both the Client and the Contractor. After a rather brief exposition of the problem and the AHP, the participants were given forms to fill in with their personal comparison results. These were then e-mailed to the senior author who made the evaluation using the commercial software ExpertChoice. At this stage there were rather many internal inconsistencies discovered, which had to be resolved by returning the forms for a renewed comparison. A total of 14 answers were obtained.

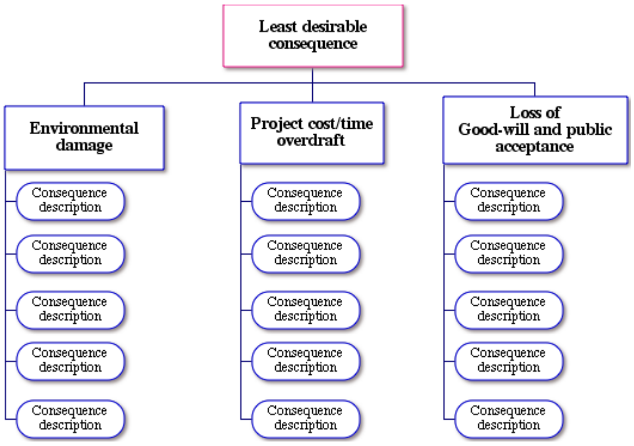

Figure 3. AHP structure used at the Hallandsås Project

It was found that the top level comparison, between the different categories, had such a large variation between the participants that it was deemed unusable. The reason was judged to be that this comparison is made regardless of the severity of the consequence. A repeated comparison was therefore made where the consequence categories were compared at each severity level.

4.2 *Results*

In Table 1 the calculated weights for the consequence classes within each consequence category together with the coefficient of variation and the ratio between the weights.

From Table 1 it can be seen that the coefficient of variation (CoV) is much larger for the "Loss of Goodwill" category than for the other two, even though "Environmental damage" is also only verbally described, without any figures. Probably "Loss of Goodwill" is more open for personal interpretations. It can also be seen that there is a subjective factor in the comparison. The category "Cost/time overdraft" is defined numerically, so there are "objective" ratios. However, these do not coincide with the ratio between the subjective weights, see Table 2. The consequence class descriptions define both the cost and the corresponding amount of time. The mean for each class has been used (for catastrophic twice the stated lower limit was used).

It can be seen from Table 2 that the classes were not well calibrated to begin with and that the assessed weights do not follow the "objective" weights. The results from the comparison between categories at different levels of severity are shown in Figure 4.

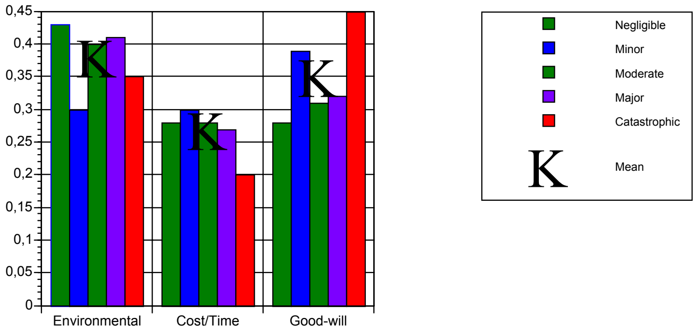

Figure 4. AHP weights from comparison between consequence categories at different consequence classes.

The high weight for loss of goodwill at the catastrophic level is due to the consequence class stating that the project must be abandoned due to severe loss of goodwill. It should also be noted that it had not been made very clear that the consequence categories other than Cost/time overdraft should not consider the purely economical loss.

Using the inter-category weights and the weights for the different categories one can calculate the weight for each consequence class relative to the top event. These weights are the category class conversion factors, see Table 3.

Table 1. Inter-category weights for the different consequence classes.

	Consequence category								
	Environmental damage			Cost/time overdraft			Loss of Goodwill		
Consequence class	**Weight**	**CoV**	**Ratio**	**Weight**	**CoV**	**Ratio**	**Weight**	**CoV**	**Ratio**
Catastrophic	0.51	12 %	1.99	0.55	9 %	2.00	0.45	29 %	1.72
Major	0.26	22 %	1.74	0.27	16 %	2.90	0.26	56 %	1.46
Moderate	0.15	32 %	2.97	0.09	28 %	1.85	0.18	68 %	2.52
Minor	0.05	34 %	1.24	0.05	18 %	1.42	0.07	33 %	2.01
Negligible	0.04	22 %		0.04	29 %		0.04	50 %	

Table 2. Cost/time overdraft. Objective and subjective ratios.

Consequence class	AHP Weight ratio	”Objective” Cost ratio	”Objective” Time ratio	Class description
Catastrophic	2.00	3.60	3.40	Delay more than 6 months or cost >100 MSEK
Major	2.90	9.20	5.60	Delay 1 month – 6 months or cost 10 - 100 MSEK.
Moderate	1.85	4.80	5.00	Delay 1 week – 1 month or cost 2 - 10 MSEK
Minor	1.42	5.00	5.00	Delay less than 1 week or cost 0.5 - 2 MSEK.
Negligible				Delay less than 1 day or cost < 0.5 MSEK

Table 3. Conversion factors.

Environmental damage	Mean	CoV	Ratio
Catastrophic	0,19	32%	1,92
Major	0,10	43%	1,80
Moderate	0,06	42%	2,96
Minor	0,02	46%	1,27
Negligible	0,01	32%	
Cost/Time overdraft			
Catastrophic	0,15	75%	2,01
Major	0,07	71%	3,06
Moderate	0,02	64%	1,79
Minor	0,01	66%	1,40
Negligible	0,01	73%	
Good-will			
Catastrophic	0,17	42%	2,01
Major	0,08	47%	1,22
Moderate	0,07	77%	2,64
Minor	0,03	51%	2,03
Negligible	0,01	56%	

4.3 *Comments and recommendations*

It was found that it is very difficult to use the AHP method with the tested procedure. There were misunderstandings and problems with interpreting the wording of the consequence class descriptions. We recommend that:

- One starts with a matrix that is as well calibrated from the beginning as possible
- The AHP is done as a group exercise lead by a risk analyst
- Have people from different parts of the project management
- Make the comparison between the categories at each consequence class

5 TESTING AHP METHODOLOGY AT THE CITY LINE (CITYBANAN) PROJECT

5.1 *The project*

The City Line is a double-track railway with two new stations that is to be built in an approximately six kilometre long tunnel passing right under the central parts of Stockholm. It is still at the planning stage.

5.2 *AHP procedure*

The risk matrices used are somewhat different from those used at Hallandsås, with five consequence categories; Human injuries, Environmental damage, Damage to societal functions, Cost overdraft and Loss of Goodwill, each with five consequence classes. As was the case at the Hallandsås Project, Human injuries were not a part of the AHP comparison. Drawing on the experiences from the Hallandsås Project the following procedure was used:

- The existing consequence class definitions were reviewed and adjusted before the session
- The AHP comparison was made as a group exercise with the senior author as moderator.
- The evaluation was done immediately and the results presented to the participants
- The comparison between the categories was made at the two highest consequence classes

The assessment was made in a manner comparable to that at Hallandsås Project:

1. Comparison between the categories without regard to the consequence class
2. Comparison between the consequence classes for each category
3. Comparison between categories at different consequence classes (the two most serious)

5.3 *Results*

The AHP weights for the different categories for steps 1 and 3 above are shown in Table 4. The high values for “Loss of goodwill” at the “Catastrophic” class are due to the same reason as at the Hallandsås Project, the consequence is an abandoned project. For the different consequence classes the results are shown in Table 5. Table 5 shows the same thing as Table 4, i.e. the heavy weight for catastrophic loss of goodwill. This was commented upon at the meeting and it was suggested that the consequence class Serious should be adjusted to make the ratio smaller.

Table 4. AHP weights for different categories. City Line.

	AHP weights		
Consequence category	**No regard to Consequence class**	**Consequence class: Catastrophic**	**Consequence class: Serious**
Environmental damage	0.196	0.141	0.340
Damage to societal functions	0.528	0.112	0.239
Cost overdraft	0.146	0.080	0.140
Loss of goodwill	0.130	0.666	0.281

Table 5. AHP weights for different consequence classes. City Line.

	Consequence category								
	Environmental damage		**Damage to societal functions**		**Cost overdraft**			**Loss of Goodwill**	
Consequence class	**AHP weight**	**Ratio**	**AHP weight**	**Ratio**	**AHP weight**	**Ratio**	**"Objective ratio"**	**AHP weight**	**Ratio**
Catastrophic	0.501	1.90	0.513	1.76	0.554	1.93	3.6	0.661	3.93
Serious	0.264	1.74	0.291	2.39	0.287	4.10	10.0	0.168	1.83
Large	0.152	2.76	0.122	2.60	0.07	1.40	10.0	0.092	1.88
Small	0.055	1.90	0.047	1.68	0.05	1.28	11.0	0.049	1.63
Negligible	0.029		0.028		0.039			0.03	

It can also be seen that the AHP weight ratios for Cost overdraft differ from the "objective" ratios as was the case at the Hallandsås Project, see Table 2. One reason might be that smaller costs are regarded as unimportant and rather equal and another that Cost overdraft as such might have been regarded as somewhat less important during the assessment. Still there is a difference, which is not easy to explain.

5.4 *Comments*

Using the group assessment approach, it was possible to discuss the definitions and also to have questions about the method immediately answered. It was also possible for participants from different areas to put forward their views and to have them paid regard to. The participants concluded that the method gives a good insight into the problem and that it is a good base for making adjustments in the consequence class description and rechecking them.

6 TOTAL RISK AND ALLOWABLE RISK EXPOSURE

6.1 *Risk budget*

It is common within the construction industry that a risk budget or a contingency is added on to the expected cost for the works. From a contractors viewpoint this is normally done already during the tender stage and is then forwarded throughout the project. Also clients and owners add such contingencies related to risk in early stages of a project.

Such contingency shall principally cover for two types of events, uncertain quantities (e.g. salary increases, uncertain material costs and additional work) and unexpected events ("accidents"). To our knowledge and experience the follow up of such risk budgets are not always stringent and there is a need to relate the total current risk exposure to the contingency to establish an allowable additional risk exposure.

There are basically two different types of risk budgets, the purely monetary budget and budgets for moral/ethical values such as human injuries, environmental damage etc. We like to point out that according to the authors, one should divide the budget for the latter type of damages into two parts, one being the monetary cost incurred by the damage. This should be added to other monetary cost consequences connected to a risk.

Whether to add all consequences into one single using the conversion factors discussed above or if one should have different risk budgets for each consequence category has at the time of writing not been studied at depth.

The authors are of the opinion that at least human injuries be treated separately and that risks entailing human injuries should always be treated using the ALARP principle. According to Ekholm (2006) it is possible to have a project risk budget for human injuries.

6.2 *Effect of risks that realise*

In the following discussion we concentrate on monetary risks.

The risk budget ought to be based on the total expected cost. This means that when Risk *i* realises, the remaining risk budget is lessened by an amount 1/P(*i*). For a single project this should be considered, and the decisions about raised demands on risk mitigations. One possible tool to help the project management might be a Monte Carlo simulation of the possible outcomes of the total exposure.

Not only has a risk that realises a direct effect on the risk budget, there is also an indirect effect caused by an increase of the remaining risks. This is illustrated qualitatively in Figure 5.

In Figure 5, the total risk exposure consists of three risks A–C. If the risk A realises, there is a direct loss of C(A), but there is also an indirect effect in that the remaining risks are increased by the amount ΔB and ΔC. These additional amounts can have different causes and are probably most often decreasing with time. Possible causes include, especially for goodwill and environmental damage, a large part of suspicion against the project and the capacity of those involved to estimate consequences and probabilities correctly. Such increases are probably exponentially decaying, c.f. Björkman (1987) who studied retention of knowledge. Another cause for the increase is a systematic bias in the assessment of probabilities in the risk management work. Such increases do not diminish with time unless there is a reassessment of the probabilities.

The subject of risk increase caused by realisations of other risks has been addressed only qualitatively, but should be studied further.

7 CONCLUSIONS

A method to describe and analyse the total risk exposure in large infrastructural projects has been outlined. The method is not yet fully developed but has, despite the complexity of the problem, proven feasible and has a potential of giving decision-makers a better tool for risk management.

Conclusions from the study presented indicate that, in order to describe a valid total risk exposure based on a transparent measure, there is a need for using risk matrices that are calibrated and that this calibration can be done by using the Analytic Hierarchy Process. Practical use of the AHP method shows that biases will be large without detailed information about the purpose and principles of the methodology. A more consistent and true result will be achieved if pair-wise comparison, to establish weight factors, is done openly and jointly in a group of experts and decision makers reaching consensus.

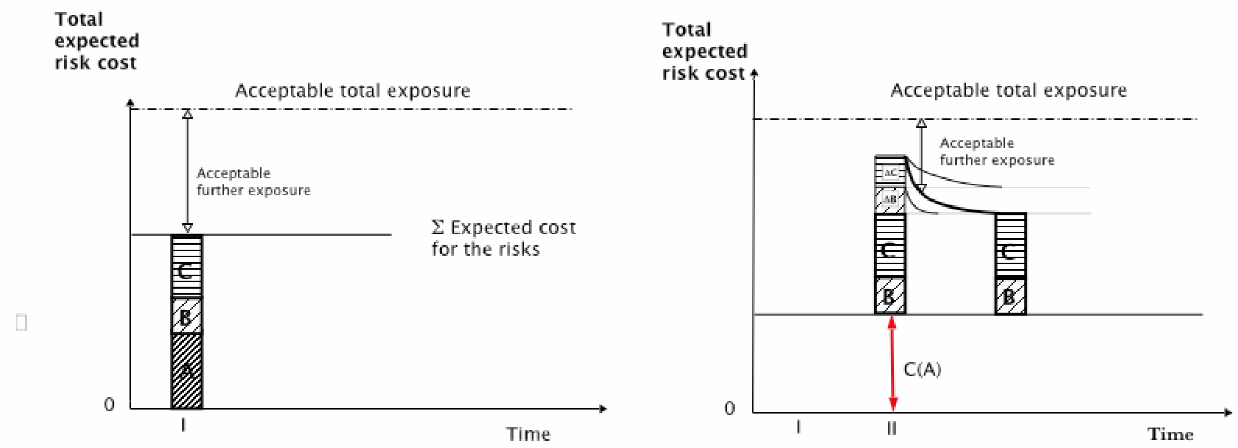

Figure 5. Effect of the realisation of a risk on remaining risks. Left diagram shows the situation before any of the risks has been realised. Right diagram show the situation after Risk A has occurred.

Weight factors for different risk categories, resulting from AHP studies, can be used to calculate total risk exposure, e.g. using the sum of expected losses, within a project or part of project.

Furthermore it has been shown that one or several risks that have realised will impact the total risk exposure, often in a negative way, leaving lesser margin for further events. It is suggested from experience that this impact is time dependant and adds a dynamic dimension to the risk management process.

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