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On the use of the 'Return Of Safety Investments' (ROSI) measure for decision-making in the chemical processing industry

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ABSTRACT

Due to the high potential of chemical and process industry to damage people, as well as to cause environmental contamination, there is a need of objective criteria and methods supporting plant operators to make decisions and optimise investments in safety measures. Currently, the use of risk-based approaches is popular in order to prioritize criticalities, based on the results of risk assessments; this approach is usually combined with cost-benefit analyses that provide criterions in the decision-making process. A commonly used framework to prioritise safety measures is based on the calculation of the *return of safety investments* (ROSI), which quantifies the expected return of the investment in safety with respect to the invested resources. In this paper the usefulness of such a framework is discussed and the need for an extension is shown using a case-study from the chemical processing industry. The study concluded that the ROSI should be used with caution, because it does not give a sufficient weight to uncertainties as it is based on the use of expected values. Some improvements to the framework are suggested, i.e. the assessment of ROSI given an accidental event and to highlight the importance of reflecting the strength of knowledge on which the ROSI metric is based.

1. Introduction

The experience from the process industry clearly shows that there is a need, especially in the field of safety, to have objective criteria and methods to optimise investments [23]. This is particularly important in the chemical sector, where hazardous materials are stored and processed with the potential of major accidents and thus to cause damage for people and workers, as well as environmental contamination ([26, 27], [25]). The assessment of risk is fundamental to establish effective safety measures in contrasting accidental scenarios, in this setting it should be highlighted that their selection poses costs and often resources are limited [1]. In addition, it should be pointed out that, while expenditures for organisational or technological improvements have always been recognised not only as disbursements but also as investments for the improvement of the efficiency and/or the effectiveness of processes, safety expenditures have been previously perceived only as costs. During the last few decades, as the awareness towards risk analysis increased, safety expenditures have been finally recognised as investments having a return for the company [29, 36]. The gain (benefit), associated with investments in safety, is attributable to the safeguard of health and environment, i.e. it is associated with savings expressed in terms of reduction of costs for accidents, the substitution of personnel, medical expenses, the company reputation, etc. [17, 35, 39]. This change extended classical financial approaches (calculating the return on investment), which were no longer considered appropriate to deal with safety-related investments, because such type of expenditures does not produce direct benefits. Based on this consideration, the monetary value of the investment started to be compared with the monetary value of the risk reduction [34].

In general, risk-based approaches are very useful in defining a priority amongst criticalities in chemical industry, as well as safety initiatives; their use support in justifying new investments by means of the demonstration of their return in terms of gained benefits (injuries cost reduction, repairing cost reduction, image enhancement, etc.). Risk-based approaches are very popular due to the widespread diffusion of the American Petroleum Institute standards ([7], [7]a), some

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applications for decision making can be found in the literature [14, 31, 37, 38]. As mentioned above, a further concern is the availability of resources to be invested, particularly when a difficult economic crisis is under way; in such cases the use of a structured approach, based on the definition of the *return of safety investments* (ROSI), provides a strong support to managers dealing with safety [28]. ROSI is the result of assessing the return of an investment in safety measures with respect to the investment itself [32]; its use allows better allocating expenses and obtaining the approval of higher budgets to increase safety. It has not to be confused with the ROI (*return of investment*) measure, applied in the financial field [13, 16], as ROSI deals with an investment that will not produce revenues.

Even if the use of ROSI appears a useful framework for the prioritisation of safety measures [34], in this paper, some extensions to such a framework are proposed based on some considerations that question its application. These considerations can be summarised in following questions: to what extent the use the ROSI metrics is appropriate as a basis for the prioritisation of safety measures? how can safety measures be prioritised along the principles of precaution and robustness, when attention is paid to traditional calculations? These points are relevant if one considers that safety investments are often embedded with a high degree of uncertainty and poor knowledge and that consequences of accidents could be significant. Based on these evidences, ROSI should be used with caution, as limited weight is given to uncertainties and the significance of accidental events (consequences). Accordingly, safety investments with a small probability of producing a high return, relative to the investment cost, could be assigned to a lower priority than other measures without such potential. To better reflect these aspects and, thereby, gain a better understanding of the return of the investment in safety measures, it has been suggested also including assessments of the potential return of safety measures relative to the investment cost, i.e. assessments conditional on an accidental event. A better foundation for prioritisation of safety measures is then given.

The starting point for our work, that one needs to reflect the relevance of information availability and knowledge, and system variability, and as such include a broad range of aspects when analysing safety situations by the use of expected value theory. The focus beyond just one aspect means that stronger weight should to be given to the uncertainties than what is made through traditional expected value calculations, reflecting the main message in the textbooks 'Operational Safety Economics: a practical approach focused on the chemical and process industries' by Reniers and Van Erp [30] and 'Safety Risk Management: Integrating Economic and Safety Perspectives' by Engemann and Abrahamsen [20]. See also Abrahamsen et al. [3] and Aven and Renn [12].

The paper has the following structure. In Section 2, a short review of the ROSI metric is given. In Section 3, the framework based on the use of ROSI for prioritising amongst safety measures is discussed. Special attention is paid to how uncertainties, strength of knowledge and accident potential are taken into consideration within the ROI calculations. In Section 4, some possible improvements of a traditional framework are proposed and discussed by using an example from the chemical industry. Finally, in Section 5, some conclusions are drawn.

2. Return of safety investments

The ROSI measure quantifies the expected return EX of a safety investment with respect to the resources invested, i.e. the expected investment cost EC. Mathematically, the measure is expressed as:

$$\mathrm{ROSI} = \frac{\mathrm{EX} - \mathrm{EC}}{\mathrm{EC}} \tag{1}$$

For long-term investments, the inputs should also be adjusted for discounted cash flow, where a discounted ROSI is quantified, similar to traditional net present value calculations. Generally, for a project, when ROSI > 0, the investment is found attractive as then the expected return of the safety investment is higher than the cumulated EC. Meaning that when comparing two investments, the ROSI can be used to point to which alternative is expected to represent the best investment.

Note that often the input is available as non-economic values, and not as monetary values as it is needed for the ROSI calculations. Hence it could be necessary to transform the different attributes into monetary values. All of the attributes, including e.g. number of accidents and number of critical failures, all needs to be expressed in monetary values. An example is given below.

Let us say a chemical factory considers installing a new safety device, depending on the results from the ROSI calculations. The expected cumulated cost (EC) of the investment is 2.0 million USD. Estimates produced show that by installing such a device, the expected number of fatal accidents is reduced by 0.8. Hence, the calculated expected benefit (EX) expressed in monetary values is then 3.2 million USD. This is based on a fixed value of a statistical life of 4 million USD; being the maximum amount one is willing to pay to reduce the number of expected fatalities by one. Using the inputs, we calculate a ROSI equal to 0.60. It means basically that the expected return is 0.60 USD for every USD we spend on the investment. With a positive return of 0.6, the measure would be implemented.

There are several examples in literature, where of assessments of ROSI are used to support safety decision-making in different industries; see e.g. [18, 22, 40], and [32]. All of these indicate that normally the ROSI is combined with also other information of relevance to the investment problem such as project specs, key performance indicators, ENPV calculations, and sensitivity analysis. In addition, as pointed to in Bansal et al. [33], the calculation of ROSI (or ROI) could give special weight to the uncertainties, to better reflect risk-averse behaviour, even if this contrasts with the traditional way of performing the calculations.

A rationale for using ROSI to measure the expected returns when considering a set of possible investments, is given by the well-known portfolio theory. According to the theory, a given portfolio of projects is valued equal to the expected value of this portfolio in addition to the systematic risks and the unsystematic risks; see e.g. Boardman et al. [15]. The systematic risks refer to the general movement of the market, which could move the portfolio on some direction, while the unsystematic risks come from uncertainties of specific projects. Normally, when managing a portfolio with significant number of projects, the unsystematic risks give a minimal contribution compared with the systematic risks, and it is appropriate to focus only on the latter. The use of expected values to express uncertainties is also justified by Durbach and Stewart [19], who argue that expected values such as ROSI calculated for decision problems under uncertainty is appropriate compared with results achieved from calculations using probability distributions to express the uncertainties.

For the ROSI, when placing the measure into a portfolio theory framework, focus is then on what is the expected cost of each of the investments in the portfolio and what is the expected return of these, where there is limited weight given to the unsystematic risks. Such risks could be that e.g. specific investments deviates significantly from the calculated ROSI, which could be the situation in safety context where the investments might deliver a significant effect only if any critical event occurs. It would be fully possible to capture these unsystematic risks in the ROSI calculations, but it will then cause that the expected returns to be generally lower for all the investments considered.

3. Discussion on the use of ROSI

The purpose of ROSI is to provide decision makers adequate information in order to balance the safety measure cost and potential savings from future adverse events. The method applies expected values, and consequently does not involve uncertainties, which is a key focus in any safety measure and risk assessment. To investigate the consequences, we propose four issues to test ROSI.

Firstly, we examine the consequence of extreme events that may be ignored when applying expected values in the calculation of ROSI. Secondly, we confront the difficulty of providing monetary values to all attributes when estimating ROSI. Thirdly, we look at the uncertainties typically hidden in the background knowledge, like assumptions and presuppositions, and the potential errors this may cause to the expected ROSI estimation. Finally, we question the corporate procedures when calculating ROSI, which may have portfolio considerations.

In the following, we describe the four challenges in detail.

3.1. Extreme events do not align with expected value calculation

Applying the expected value to calculate ROSI will ignore the extreme adverse events the investment intends to safeguard. This is particularly of importance to safety measure calculation, where the less probable outcomes typically have a highly negative cost, i.e. death and injury of personnel or severe damage to machinery. By ignoring this, the calculation of ROSI may cause poor predictions of possible outcomes. To further illustrate this, we use an example. In general, when applying ROSI or any other investment method, the decision maker requires a positive expected (present value) return to execute the investment. Assume the investment cost is 100 million USD for a safety measure which safe guards one particular negative event that will cost the company 10 billion USD if it occurs. However, the probability of this event is estimated at only one to a thousand (10−3), and otherwise the return from the investment is zero. Consequently, the expected return from the investment is

$$10^{-3} * 10^{10} + \left(1 - 10^{-3}\right) * 0 = 10^{7} = 10 \ \textit{million USD}$$

Consequently, the calculated ROSI is −0.90, and the proposed investment will not be executed. However, by treating the two scenarios individually, there is a 10−3 or 0.001 chance that ROSI is equal to 99.00 and a probability of 0.999 that there is no return on the investment and ROSI is equal to −1.00.

The example illustrates the problems of only emphasizing the expected value, as we ignore the potential negative outcome or the unsystematic risk. Said in another way, we ignore the potentially high ROSI from the adverse event. Aven [8] and Abrahamsen et al. [3] support the same argument, when arguing that portfolios need to include these unlikely extreme losses, as the consequence of this extremely negative outcome will hurt the portfolio and/or company to a severe degree.

3.2. Not all dependant variables are easily converted into monetary values

The estimation of ROSI depends on putting a monetary value on all its depending variables. This is necessary in order to compare cost, risk and the potential savings from the investment. Moreover, it provides consistency and transparency and an important part of a decision-making process is to set a monetary value to each outcome and risk. Merkhofer [24] and Abrahamsen et al. [2] argues that these transformations are reasonable to arrive at an economically based decision.

However, putting a monetary value on all variables related to a safety measure is difficult as it typically involves non-market goods. The negative outcome of a risk may involve the potential loss of life, injuries or other health repercussions, as well as environmental issues or reputational damage, which the safety measure intends to protect. Consequently, a monetary approach may be to limiting. An example may provide the intuition for these non-market goods and the problem of setting an objective monetary value. If a person were asked to put a value for their own life, the monetary value would be infinity as most people would not be willing to sacrifice their life for a certain amount of money. In short, an objective value does not exist for a person's life. This emphasises that when prioritising investments using ROSI, it is important to take into account consequences beyond the estimated ROSI and its monetary values.

3.3. Unaccounted background knowledge cause extra uncertainty

According to Flage and Aven [21], background knowledge includes assumptions, information, data, phenomenological understanding, models and expert opinions. The expected values used to calculate ROSI are conditional on the background information, K. Consequently, we may redesign the expression for ROSI (Eq. (1)) to:

$$\mathrm{ROSI} = \frac{\left(\mathrm{E}\left[\mathrm{X}|\mathrm{K_i}\right] - \mathrm{E}\left[\mathrm{C}|\mathrm{K_j}\right]\right)}{\mathrm{E}\left[\mathrm{C}|\mathrm{K_j}\right]} \tag{2}$$

The subscripts i and j identify that the background information on which the expected benefit is conditional on is different from the background information on which the expected investment cost is conditional on.

A critical consequence of this issue, is when two analysts assessing the same safety measure come up with competing ROSI-values. Due to differences in their background information, the two analysts may even provide different conclusions as one recommends the investment while the other rejects it. From a portfolio perspective, both estimates are good, as they allow us to prioritise (accept or reject) the project. However, since the conclusions are opposites, both values cannot be true, and as such, it is difficult to follow portfolio theory, which suggests that the decision should only depend on ROSI and the systematic risk, when the conclusions are opposites. Abrahamsen et al. [1] advises to consider the potential uncertainties hidden in the background knowledge. From a ROSI perspective, the decision-maker needs to review the strength of knowledge behind the ROSI estimate.

3.4. Overall portfolio may be influenced by corporate procedures

For companies addressing multiple safety measure decisions, someone may argue that from a portfolio perspective, it is not relevant to put emphasis on background information and the possible lack of or wrong information. Their argument is that the influence from faulty background knowledge will cause a 'zero-sum' impact, as the background knowledge for some measures will have a positive contribution on the ROSI value, while other measures will have a negative effect on the ROSI value. However, from issue (c) we argue that background information may cause opposite conclusions, and consequently provide the wrong recommendation.

This is further emphasised by the fact that some background information, assumptions or presuppositions, may cause all the calculations to move in the same direction. Abrahamsen et al. [3] argue that corporate procedures, for example poor guidance documents, can contribute to a situation where all calculations are affected in one direction. As a consequence, the ROSI calculation could be misleading and cannot be used as a single measure to the decision.

4. A framework for prioritising safety measures in chemical industry

With reference to the discussions in the previous sections, there are several important aspects which need to be taken into consideration when applying ROSI to guide investments and decision-making regarding safety measures in the context of chemical industry. A general problem is that the uncertainties are not fully captured. Significant failures or accidents in chemical industry are often associated with low probabilities, making the safety measure unprofitable from a ROSI perspective. In safety management, however, the weight on the uncertainties must be placed outside the frame of expected values, implying that the precautionary principle will often have a role to play [3]. The consequences should be given greater attention than what is supported by the ROSI, to better understand what can go wrong and how the safety measure can prevent or mitigate those consequences. That is, the decision support should also address the safety performance of a

Table 1
Examples on specifications of low, medium and high ROI and ROI|A.

Category	ROSI	ROSI|A
Low (L)	ROSI < 0	0 < ROSI|A < 100
Medium (M)	0 < ROSI < 0.5	100 < ROSI|A < 1000
High (H)	ROSI > 0.5	ROSI|A > 1000

safety measure given that a critical accident (A) occurs [33]. To achieve more risk-informed decision support, we suggest that the ROSI conditional on an accident A occurring (ROSI|A) is also taken into account. By the following procedure, which is motivated by Abrahamsen et al. [5], a qualitative categorisation of the safety measures can be made to support decision-making:

1 Specification of what low, medium and high ROSI and ROSI|A imply.
2 Evaluation of the ROSI
   a) Evaluation of expected costs, E [C], and expected benefits, E [X].
   b) Evaluation of strength of knowledge, SoK, and stochastic uncertainty, U.
   c) Categorisation of ROSI with reference to the evaluations made in 2a and 2b.
3 Evaluation of ROSI given an accident A (i.e. that the measure is used), ROSI|A
   a) Evaluation of expected costs given an accident, E [C|A], and expected benefits given an accident, E [X|A].
   b) Evaluation of strength of knowledge, SoK, and stochastic uncertainty, U.
   c) Categorisation of ROSI given an accident (ROSI|A) with reference to the evaluations made in 3a and 3b.
4 Classification the safety measures with reference to the evaluations in 2 and 3.

   If multiple safety measures are given the same classification, from step 4, it is challenging to distinguish them solely on the evaluations in step 1 to 3. In such matter, the additional procedure is suggested:

1 Evaluation of safety measures with reference to a general checklist.
2 Categorisation of the safety measures with reference to evaluation in 5.

   The different steps are explained in more detail in the following.

4.1. *Definition of low, medium and high ROSI and ROSI|A*

The first step is to establish some specifications of what a low, medium and high ROSI and ROSI|A implies. This is critical in the suggested framework, as the ROSI|A is likely to be significantly larger than the ROSI for any safety measure. This issue will depend on the context, and should be considered a managerial review and judgement task. As an example, we have listed a few specifications of the ROSI and ROSI|A in Table 1. It is important that the ROSI and ROSI|A of all the safety measures being evaluated in one same decision-making process, are categorised according to the same specifications. That is, a high ROSI|A for measure X is the same as a high ROSI|A for another measure Y. But a high ROSI for measure X is significantly different from a high ROSI|A for the same measure.

4.2. *Evaluation of the ROSI*

4.2.1. *Evaluation of E [X] and E [C]*

For the sake of simplicity, we have decided to classify both the E [X] and E [C] in four categories (very low, low, medium and high). The classifications will be case specific, subject to the analyst's judgments. The output of this step is considered to be a ROSI-index, where the different combinations of E [X] and E [C] produce three different indices (low, medium and high), as presented in Fig. 1. When the expected benefits are considered to be high (low) in relation to the costs, the ROSI-index is defined as high (low). In the lower right corner, of Fig. 1, the combinations of E [X] and E [C] are categorised as high, while the combinations in the upper left corner are categorised as low. All other combinations are categorised as medium.

Care should be taken when evaluating the ROSI-index, as a ROSI analysis may produce different indices depending on what dimensions of benefits that are included in the analysis [5]. To illustrate, the expected benefits of a safety measure may relate to the benefits X1 and X2. If we then assume that the expected cost of the measure is medium and the expected benefits X1 and X2 are low and medium, respectively, the corresponding ROSI-indices will be low and medium according to Fig. 1. In terms of cautionary thinking, the ROSI-index for that measure is considered to be low.

4.2.2. *Evaluation of SoK and U*

The expected values are conditional on a background knowledge, in which uncertainties may be hidden, such as assumptions that turn out to be wrong. Surprises can also occur relative to the knowledge available [10]. To reflect the quality of the background knowledge, it is informative to evaluate the strength of knowledge (SoK) by addressing the assumptions made, the amount and relevancy of the historical data, consensus amongst experts, general understanding of the phenomena of interest, degree of model accuracy, and to what extent the knowledge K

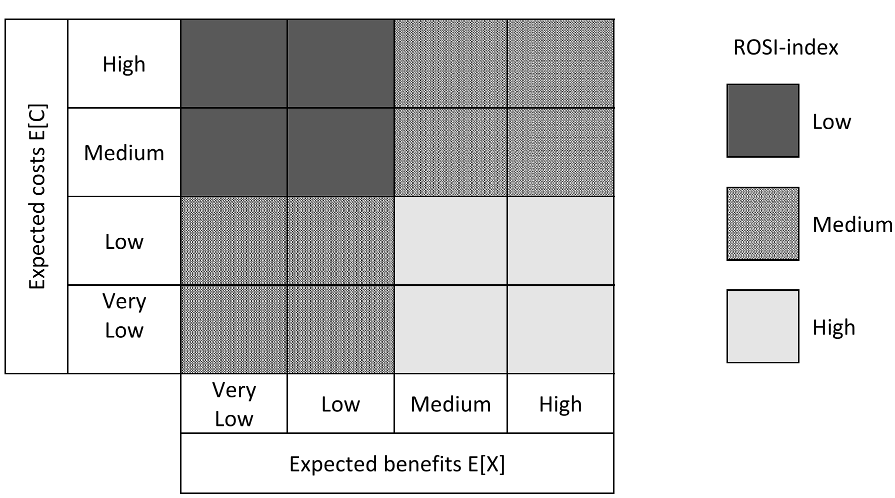

Fig. 1. Matrix representing E [X] and E [C].

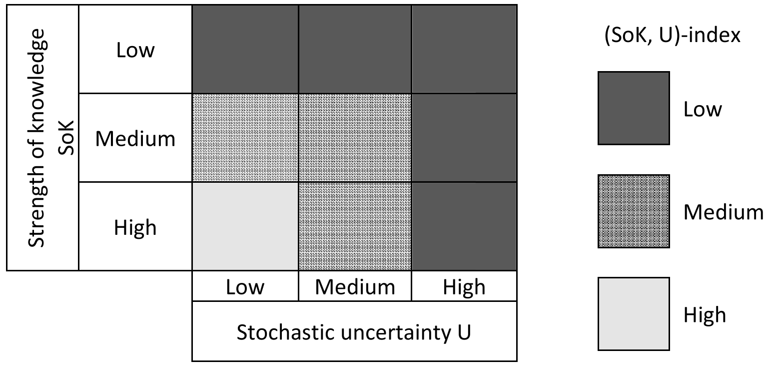

Fig. 2. Matrix representing SoK and stochastic uncertainty.

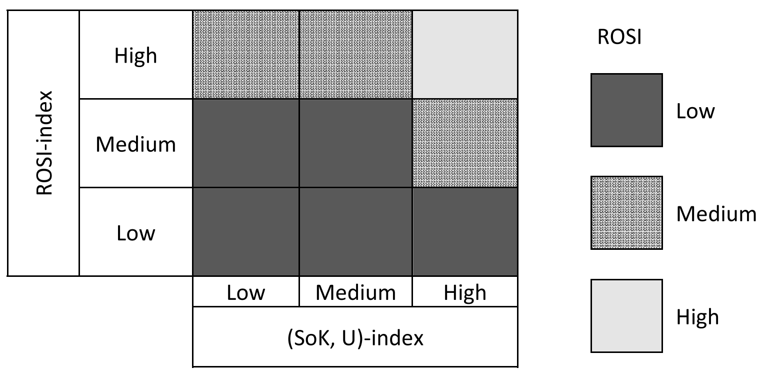

Fig. 3. Matrix representing ROSI.

has been thoroughly examined [11, 21]. In addition, a safety measure can produce a wide range of benefits (and costs), from low to the extreme [4]. Consequently, it is informative to consider the stochastic uncertainties (U), representing the expected values' prediction quality of the real benefits and costs.

Both the SoK and U is evaluated by three categories (low, medium and high). Low and high SoK and U are evaluated according to the categorisation in Table 1. Cases in between the respective categorisations are considered as medium for both the SoK and U.

To summarise the results of the SoK and U categorisation, we apply a 3×3 matrix as shown in Fig. 2. Here, the combinations of SoK and U, which can be considered as prediction quality indices [5], produce three different outputs (low, medium and high). From Fig. 2, we see that we have a high (SoK, U)-index in the lower left corner, when the SoK is evaluated as high and the U is classified as low. On the other hand, if either of the SoK or U is classified as low or high, respectively, the (SoK, U)-index is classified as low. Cases in between are considered medium.

4.2.3. *Categorisation of ROSI*

The final step is to categorise the ROSI with reference to the evaluations in 2a and 2b, for example, by a matrix as in Fig. 3. In cases of medium or low (SoK, U)-index, the ROSI is considered one category down from the ROSI-index; the matrix emphasises cautionary thinking. When the (SoK, U)-index is high, however, the ROSI and ROSI-index are considered equal.

4.3. *Evaluation of the ROSI|A*

As also claimed for ROI, the ROSI alone does not adequately reflect the real benefits of a safety measure if an undesired event occurs [33]. It is therefore informative to evaluate the ROSI given an accident occurring – that is, the ROSI of a safety measure when the safety measure is being put on demand. The evaluation of ROSI|A follows the same three steps as in the evaluation of ROSI, but with respect to the expected benefits and costs given an accident A occurring, E [X|A] and E [C|A]. For the sake of simplicity, we will only summarise these steps briefly as they are similar to steps 2a to 2c.

The evaluations of E [X|A] and E [C|A] are done qualitatively in four categories (very low, low, medium and high), resulting in three different ROSI|A-indices (low, medium and high) and are to be represented in same fashion as Fig. 1 (with the E [X|A] and E [C|A] on the x and y-axis,

Table 2
Categorisation of SoK and U. Cases in between low and high are considered to be medium.

	Low	High
Strength of knowledge [21]	One or more of the following is true: The assumptions represent strong simplifications Data is non-existent or highly unreliable There is a lack of consensus amongst experts The phenomena of interest are poorly understood; models are non-existent or known to give poor predictions	All of the following is true: The assumptions are seen as very reasonable Large amounts of reliable and relevant data are available There is a broad agreement amongst experts The phenomena involved are well understood; models are known to give accurate predictions
Stochastic uncertainty [5]	The expected values are considered to give good predictions of the real values of interest. This implies that the population has a low variation, and that it may be cases where the expected values are considered to give good predictions, despite the SoK being classified as low.	The expected values are considered to give poor predictions of the real values of interest. This implies that the population has high variation, and that it may be cases where the expected values are considered to give poor predictions, despite the SoK being classified as high.

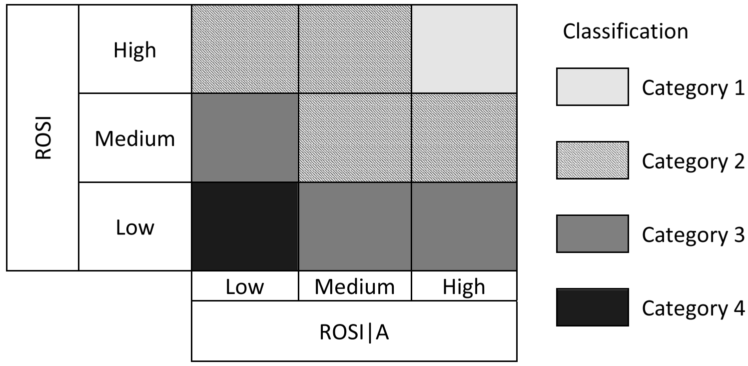

Fig. 4. Classification of safety measures with reference to ROSI and ROSI|A.

respectively). Although the expected values are conditional on an undesired event occurring, it is still paramount to see beyond the expected values. The SoK and U, with reference to the E [X|A] and E [C|A], are evaluated according to Table 2, and presented by Fig. 2. The final step is to categorise the ROSI|A with reference to the evaluations in 3a and 3b, for example, by a matrix as in Fig. 3 (but with the ROSI|A-index on the y-axis).

4.4. Classification of the safety measures

After the ROSI and ROSI|A of all the relevant safety measures have been categorised, the next step is to compare the safety measures with reference to the ROSI (step 2) and ROSI|A (step 3), by a matrix as the one shown in Fig. 4. The different combinations of ROSI and ROSI|A can produce four different categories of investments. As shown in Fig. 4, safety measures with both high ROSI and ROSI|A are classified as category 1 and are considered as the most appropriate investments. This is reasonable, as the ROSI is high, indicating that the measure is in general a good investment, and the ROSI|A is high, meaning that the benefits of the measure will be significant if an undesired event occurs.

In category 2, the safety measures are less attractive than in category 1, but still profitable investments that should be recommended. If a safety measure has a high ROSI it is in general a good investment with reference to expected values, implying that the measures will also be good investments if an accident should occur. To put weight on the uncertainties and the potential for big losses, we suggest that safety measures with medium ROSI and medium or high ROSI|A are also included in this category 2.

Safety measures in category 3 are not favourable with reference to the ROSI (low or medium). But if the conditional ROSI|A is medium or high, a low ROSI is lifted up to category 3 by the potential benefits of the safety measure should an accident occur. Finally, in the lower left corner, safety measures are classified by both low ROSI and low ROSI|A, making them the least attractive investments amongst the safety measures being evaluated.

From Fig. 4, we are able to compare the different safety measures being considered for implementation in a simple and clear way. The general idea is that, if the ROSI|A is medium or high it implies that the safety performance of the measure is in general good, making the investment more attractive than what is supported by the ROSI.

4.5. Evaluation of the safety performance of the measures of same category

One issue, however, which is likely to arise from the suggested framework, is that multiple safety measures are classified by one category (i.e. category 2 or 3) making it difficult for the decision-maker to distinguish and rank the investments. To overcome this issue, a checklist is provided for relative comparison of different safety measures of same investment category from step 4. The checklist, which is motivated by Aven [9], intends to evaluate the safety performance of the safety measures by a qualitative scoring (i.e. low, medium or high). How this checklist should be formulated is a managerial task [6], but the following gives some pointers on what criteria that can be included.

Table 3
Checklist to evaluate the safety performance of a safety measure.

Evaluation criteria	Classification
Probability of undesired event A, P(A|K)	Low/medium/high
The SoK supporting the probabilities	Low/medium/high
Reduction of the uncertainties	Low/medium/high
Manageability	Low/medium/high
Robustness	Low/medium/high
Level of the technology	Low/medium/high
Unsolved problem areas	Low/medium/high
Experience with similar accidents/measures	Low/medium/high
Other strategic issues	Low/medium/high
Overall evaluation	Low/medium/high

The first criteria that should be included in the checklist is the probability of the undesired event, P(A). The probability of an accident is the analyst degree of belief in that accident occurring, which reflects the uncertainties regarding whether the safety measure will be used [33]. A high probability implies a high need for the safety measure, and vice versa for a low probability. It is also informative to consider the SoK on which the probabilities are based.

Other criteria, which indicate the safety performance and/or need of a safety measure, are taken from the layered approach to implement the as low as reasonable practicable (ALARP) principle in safety management (see, e.g., [6, 9]). The criteria are summarised in Table 3. A safety measure with a relatively high overall evaluation is preferable, and given priority to the other safety measures. That is, a measure which, say, significantly reduces uncertainty, increases robustness and manageability, is the best available technology, and so on, is given a high overall score.

4.6. Categorisation of the safety measures of same category

Following the checklist, safety measures can be summarised by Fig. 5, with reference to the probability of the undesired event and the overall evaluation of the safety performance of the safety measure. A safety measure in the upper right corner, with high probability and high overall safety performance, is given the highest priority. If the probability of accident is low, and the overall safety performance of the measure is low, the safety measure is given the lowest priority. The priority of the safety measures is gradually increasing from the lower left corner to the upper right corner.

The additional information intends to rank projects of apparently similar ROSI and ROSI|A classification, without requiring precise quantitative evaluations. A consequence of the additional information is that we allow safety measures to alter their initial category (from step 4).

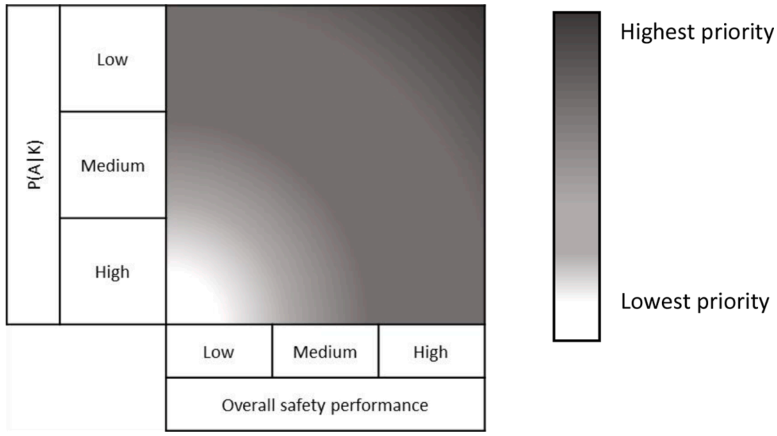

Fig. 5. Matrix for comparing the safety measures of the same investment category.

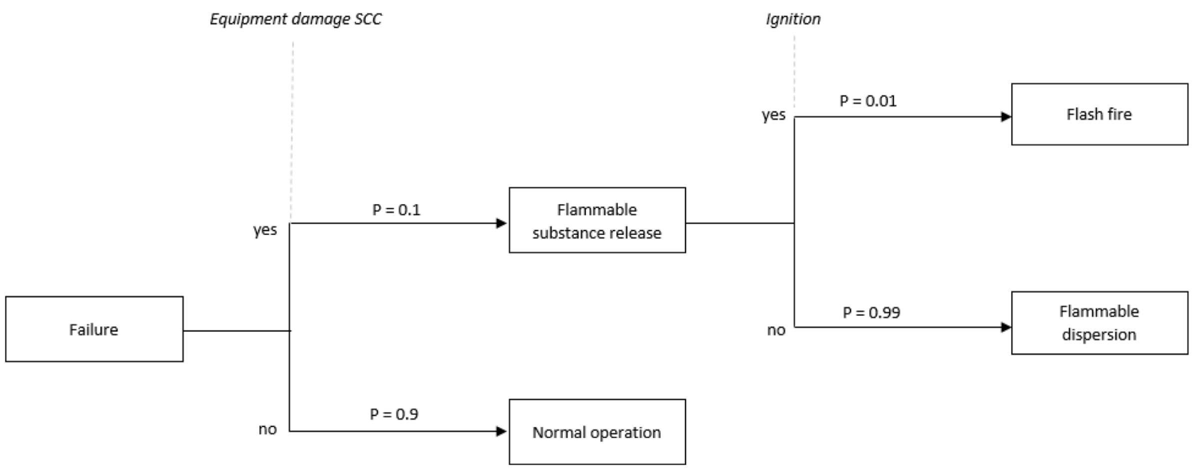

Fig. 6. Initial probability of the accidental scenario.

A safety measures with high priority according to Fig. 5, promotes a shift in its investment category. That is, a safety measure evaluated as category 3 from step 4, may be shifted up one level following step 5. Similarly, a measure may drop down one category, given the overall safety performance and/or probability of accident.

5. An example from the chemical industry

To demonstrate the usefulness of the extended framework for the ROSI application, a case-study from chemical industry has been selected. It refers to a unit of a refinery, which is used for the hydrocracking of hydrocarbons. After the treatment of heavy hydrocarbons, light products and a gaseous stream are produced. The gas contains some acid by-products, which are neutralised in an absorption column by means of an amine solution. This equipment is affected by stress corrosion cracking (SCC) due to its operative conditions. SCC is a deterioration mechanism causing the growth of crack formation due a corrosive environment. The column contains hazardous materials, therefore, it could be a potential source of dangerous releases in the atmosphere, in case the damage mechanism is not properly controlled. The most significant hazard is the formation and ignition of a flammable cloud.

The probability of this event (flash fire) is estimated to be $1\bullet10^{-3}$ event/year (see Fig. 6). A more complete assessment should include a pool fire, a flash fire, a dispersion and an explosion, as identified scenarios in case of a release. As indicated in the Safety Report of the Company, the explosion is considered not credible due to the absence of congested areas around the facilities, whereas the pool fire has very negligible effects due to the presence of a containment basin that limits the spread of the released product in the surrounding. The plant management decides to invest resources in preventing and mitigating the consequences of the release. Hence, in addition to the current safety expenses (see first column of Table 4), two further solutions have been

Table 4
Safety expenses.

Safety expenses	Cost (USD)
Process safety study including AtEx study	10,000
Legal requirements	2500
Creation of Safety Report	7000
Control instrumentations - solution (i)	10,000
Emergency buttons and shut-down systems	750
Visual inspection systems (level indicators, displays, etc.)	2000
Protective materials (cladding and lining) - solution (i)	500
Gas detection system - solution (ii)	1500
Firefighting systems - solution (ii)	2000
Collection or storage devices	2500
Collective protective system	500
Maintenance of safety devices	20,000
Start-up/shut-downs	3000
Creation of safety procedures	500
Emergency systems	2500
Transportation of hazardous materials and documentation	10,000
Process safe contractors (selection, training and loss of work for training)	15,000
Total	94,250

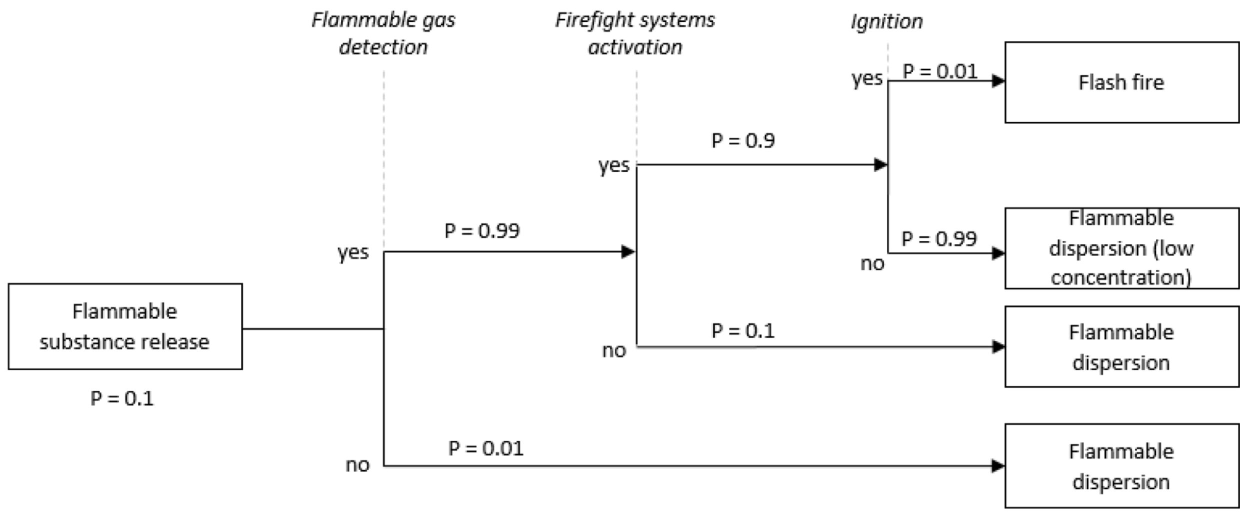

Fig. 7. Probability of the accidental scenario in case of the adoption of the solution (i).

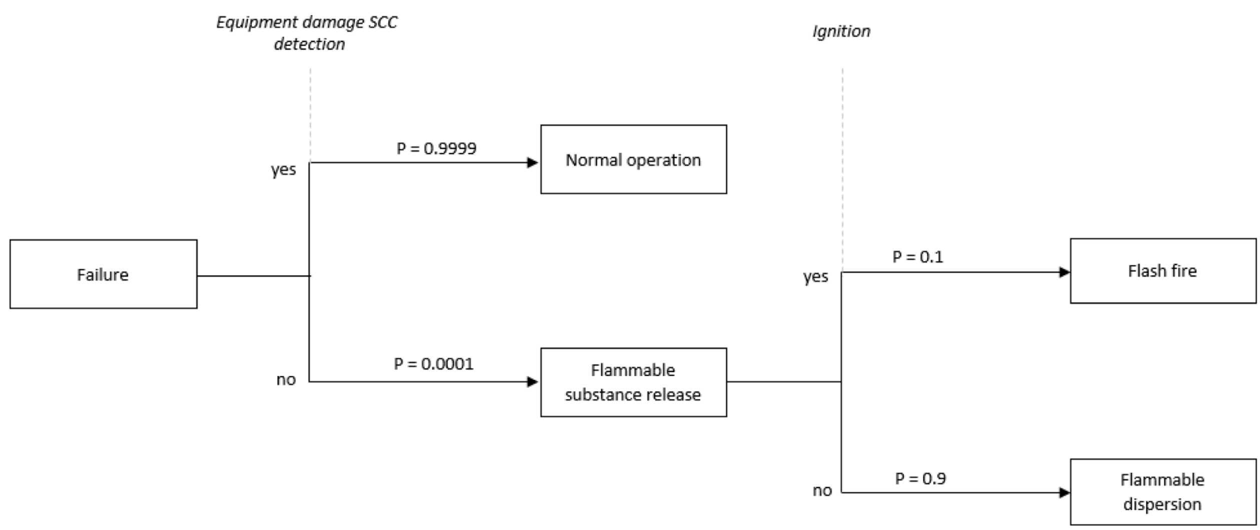

Fig. 8. Probability of the accidental scenario in case of the adoption of the solution (ii).

Table 5
Benefits.

Benefits	Cost saving (USD)
Reduction in shut down	2000
Reduction in inspection costs	10,000
Avoidance costs	250,000
Avoidance of accident investigation costs	70,000
Non staff turnover	12,000
Fatalities	1800,000
Working hours for safety and health staff, training of safety staff, working hours management and line management, benefits from medical services, investigation and measurements, benefits from external service, benefits from training and development, organisational costs	150,000
Total	2294,000

examined: i) a gas detector, which actuates some firefighting systems when the flammable release occurs, and ii) a new internal protective coating (cladding) and an innovative sensors' network. Due to the integration of the solution (i), the probability of the flash fire changes ($P_{fire} = 8.9 \bullet 10^{-4}$ event/year); as given in Fig. 7, this is due to the timely firefighter activation following the gas detection and the dilution of the cloud. The solution (ii) allows further decreasing the probability of the flash fire ($P_{fire} = 1 \bullet 10^{-5}$ event/year), as given in Fig. 8, it is the consequence of the prevention of the damage due to the SCC phenomenon by foreseeing its propagation and also the use a more resistant material, which reduce the probability of the release.

A systematic assessment of costs and benefits has been made by using the popular checklist of the HSE (https://www.hse.gov.uk/managing/theory/alarpcheck.htm), even if several tools and software are available [30].

The initial costs for safety are 78,750 USD, whereas the additional investment is 3500 USD for solution (i) and 12,000 USD for solution (ii). The costs for the implementation of these safety solutions include expense for their maintenance, installations and some training. The costs included in Table 4 are direct costs for safety; in Table 5 the "avoidance costs" are the costs avoided that are sometimes indicated ad costs for accidents. These includes several sub-costs related to the component damage (repair or replacement), the business interruption (calculated as the annual production multiplied the cost of the product), production losses, damage to the properties and the environment, cost for the damage to reputation, fines/legal costs. The cost of fatalities is the value suggested by HSE.

An average lifetime of 20 years for the whole system is assumed. By installing a new cladding, the costs for start-up and shut-down will be

Table 6
Specification E [X] and E [C] levels.

Category	E [X]	E [C]
Very Low	< 100 USD	< 10^3 USD
Low	100 USD ≤ E [X] < 10^3 USD	10^3 USD ≤ E [X] < 10^4 USD
Medium	10^3 USD ≤ E [X] < 10^4 USD	10^4 USD ≤ E [X] < 10^5 USD
High	≥ 10^4 USD	≥ 10^5 USD

Table 7
Results of E [X] and E [C].

Case	E [X] USD	category	E [C] USD	Category	SoK	U
Safety solutions (i)	40,879	Medium	21,255	Medium	High	Low
Safety solutions (ii)	459	Low	23,451	Medium	High	Low

reduced; whereas the use of a sensors' network, able to detect the progress and acceleration of the corrosive phenomenon, will provide a further reduction of the initial safety expenses. Tables 5 gives the benefits derived from safety investments over 20 years. A discount rate of 7% has been considered in the calculating the future values of the investments (except for the value of live savings).

The specification of low, medium and high ROSI and ROSI|A is assumed to be as in Table 1, whereas the categories of expected benefits and investment costs are shown in Table 6. This latter classification refers to the opinion of the analyst for the specific contest of chemical industry. In quantifying the strength of knowledge, with respect to the evolution of the mechanism of damage in leakage and subsequently in the generation of a fire, the following can be stated:

4- Formulated assumptions in studying the SCC are considered very reasonable
4- Large amounts of reliable historical data exist
4- The phenomenon is known and there is broad consensus amongst the experts
4- The model provides accurate estimates
4- The expected values are considered to give good forecasts (medium variation)

A summary of the results of the evaluation of E [X], E [C], SoK and U is given in Table 7. Finally, Figs. 9-11 show the representation of E [X], E [C], SoK, U and ROSI by using a matrix representation.

The same calculation has been done with respect to ROSI|A. A summary of the results of the evaluation of E [X|A], E [C|A], SoK and U is given in Table 8. Finally, Figs. 12-14 show the representation of E [X|A], E [C|A], SoK, U and ROSI|A by using a matrix representation.

The comparison between the safety measures is given in Fig. 15 by using the outcomes from the evaluation of ROSI (Fig. 11) and ROSI|A (Fig. 14). Without the consideration of ROSI|A, safety solution (i) represented the best investment as it had a higher expected ROSI than safety solution (ii) (Fig. 11). This information, however, did not address or reflect the safety performance of the two measures if they should be put on demand. In contrast to the ROSI evaluations, the ROSI|A evaluation indicated that safety solution (ii) would have a higher return on investment if an accident should occur compared to safety solution (i). As a result, the two measures were classified by the same priority category (Fig. 15), and further analysis should be carried out to rank the two

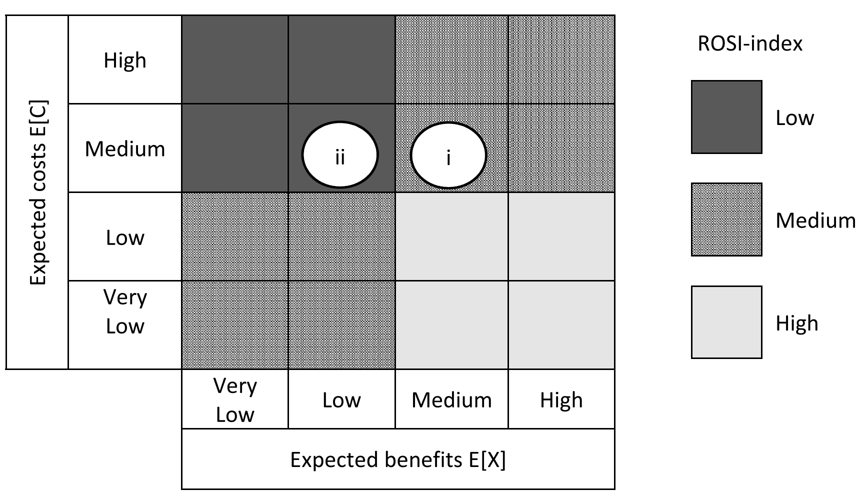

Fig. 9. Matrix representing E [X] and E [C].

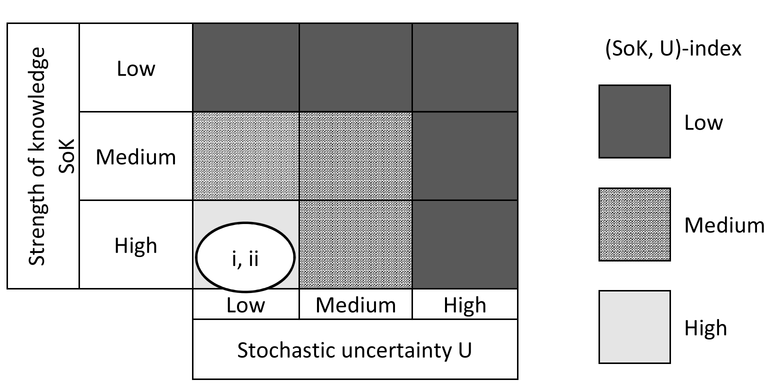

Fig. 10. Matrix representing SoK and U related to Fig. 9.

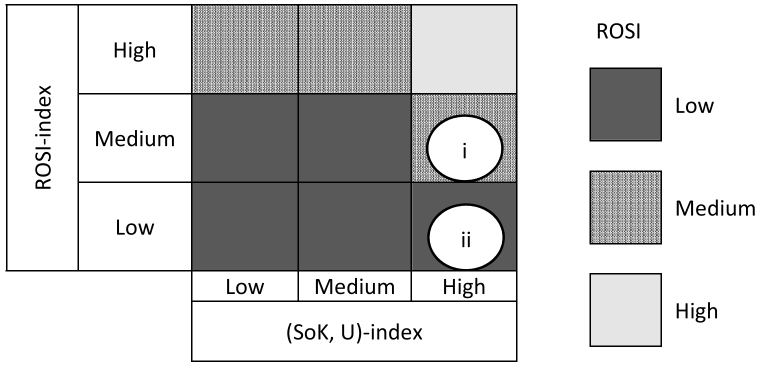

Fig. 11. Matrix representing ROSI.

Table 8
Results of E [X|A] and E [C|A].

Case	E [X|A] USD	category	E [C|A] USD	Category	SoK	U
Safety solutions (i)	409	Low	21,255	Medium	High	Low
Safety solutions (ii)	$4.59\ 10^{6}$	High	23,451	Medium	High	Low

measures (for example by following step 5 and 6 in Section 4). In this example, we have not ranked the two measures, as it should be considered a task for managerial review and judgement, in which the background knowledge should be taken into account.

6. Conclusions

Although there are some challenges, use of ROSI generally represents a useful way to compare different safety investment alternatives. The calculations are simple and straight-forward and make the measure highly attractive in safety-related decision-making. At the same time, it should be noted that the challenges addressed in this article, coming mainly from insufficient weight on uncertainties, may compromise the decision quality. The example serves as a good illustration of that. Hence, it is important that the uncertainties, and also the effects given that there actually is a demand (i.e. vulnerability), are reflected in some way when the measure is used to inform safety decisions in the chemical industries.

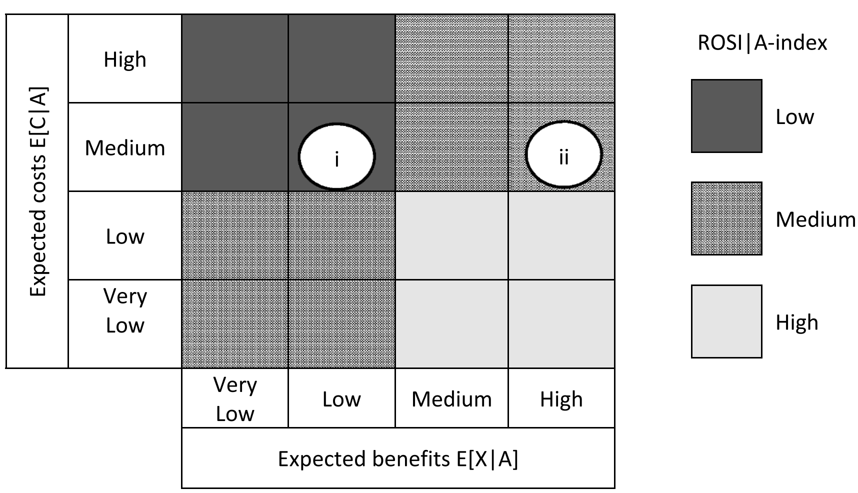

Fig. 12. Matrix representing E [X|A] and E [C|A].

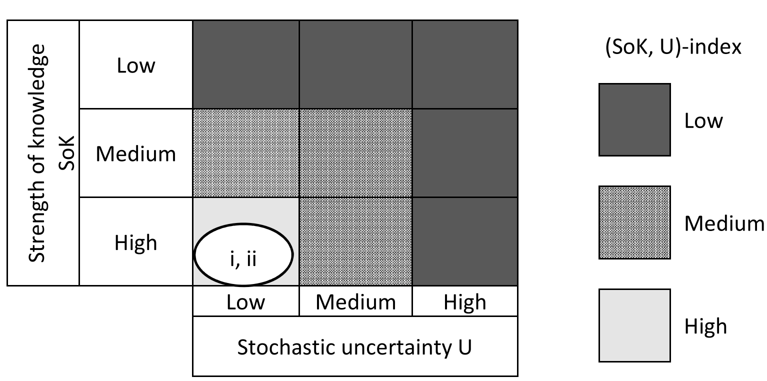

Fig. 13. Matrix representing SoK and U related to Fig. 12.

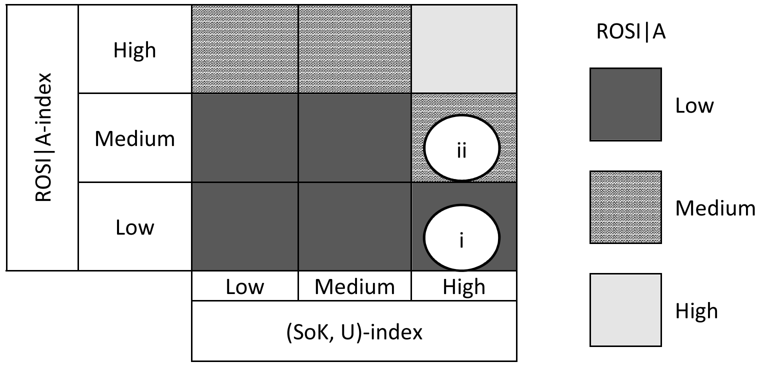

Fig. 14. Matrix representing ROSI|A.

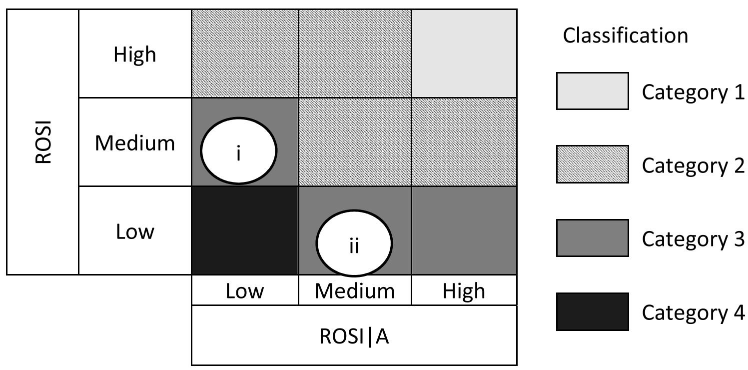

Fig. 15. Matrix representing the classification of the safety measures.

A recommendation in this article is that ROSI should be complemented with key information about how assumptions and the strength of knowledge influence the results, this beyond what is given from traditional sensitivity analysis. The idea is that this information comes as a supplement to the information provided by the conditional ROSI; i.e. the expected return given an accident A occurring, E [X|A], and should also cover assumptions related to this value. Broadening the framework to capture an extended set of ROSI elements, is a simple yet informative way of adding weight to uncertainties in the assessment of ROSI.

In the chemical industries, a broader framework allows for higher attention to situations where the safety investments could have a significant effect, while not disregarding the probability of the accident event to occur. Consequently, the framework gives higher focus to extreme events, as the investment preventing such events are seen as more fruitful. It allows for a link between consequence identification or vulnerability assessment, and fault tolerance. Extreme event situations could otherwise be somewhat hidden in the results. And by broadening the framework, focus on such events is achieved without adjusting the traditional ROSI measure in any way.

There are several arguments for why it is important to broaden the framework. First; as already mentioned, it is important to consider the uncertainties in better way. The recommended adjustments allow for higher attention to the strength of the background knowledge and its influence on the ROSI results and conclusions, including also the effect of ‘corporate procedures’. Second; expressing ROI results by single numbers provide a too narrow picture of the expected returns, and is better expressed using probability distributions, e.g. through Monte Carlo simulations. Generally, when calculating expected values, it is important to express the uncertainties beyond what is given by only the expected value. Third; the calculations of the extended ROSI, similar to the traditional way, require all attributed to be expressed in monetary values. Meaning that challenges addressing difficulties in doing so is still there. However, assessments of assumptions and sensitivity adds higher attention to them when evaluating the results.

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Declaration of Competing Interest

There are no conflict of interest.

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