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Multi-criteria decision-making considering risk and uncertainty in physical asset management

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A R T I C L E I N F O

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A B S T R A C T

In this work we present a method for risk-informed decision-making in the physical asset management context whereby risk evaluation and cost-benefit analysis are considered in a common framework. The methodology uses quantitative risk measures to prioritize projects based on a combination of risk tolerance criteria, cost-benefit analysis and uncertainty reduction metrics. There is a need in the risk and asset management literature for a unified framework through which quantitative risk can be evaluated against tolerability criteria and trade-off decisions can be made between risk treatment options. The methodology uses quantitative risk measures for loss of life, loss of production and loss of property. A risk matrix is used to classify risk as intolerable, As Low As Reasonably Practicable (ALARP) or broadly tolerable. Risks in the intolerable and ALARP region require risk treatment, and risk treatment options are generated. Risk reduction benefit of the treatment options is quantified, and cost-benefit analysis is performed using discounted cashflow analysis. The Analytic Hierarchy Process is used to derive weights for prioritization criteria based on decision-maker preferences. The weights, along with prioritization criteria for risk reduction, tolerance criteria and project cost, are used to prioritize projects using the Technique for Order Preference by Similarity to Ideal Solution. The usefulness of the methodology for improved decision-making is illustrated using a numerical example.

1. Introduction

In the last decade, the management of physical assets has emerged as a crucial business function for companies operating in asset intensive industries. Furthermore, the complex nature of modern engineered systems has led to the need for physical asset management as a discipline (Hastings, 2015). Complex systems, composed of many interacting and inter-dependent components are increasing the likelihood of extreme, rare and disruptive events (Komljenovic et al., 2016). As such, it comes as no surprise that the ISO 55000 Asset Management series of standards emphasize the need for risk-informed decisions (International Standards Organization, 2014).

Risk assessment in the asset management context requires the identification of what can go wrong (e.g. unexpected asset failures), characterization of the likelihood and consequence of such events, and comparison of the likelihood and consequence against risk tolerability criteria to determine risk treatment options (International Standards Organization, 2018). Treatment options give rise to potential asset investments that must be prioritized while taking into consideration several factors (e.g. cost, return on investment, risk tolerability, etc.). In this work we present a framework and methodology for quantitative prioritization of risk-informed asset management projects using multi-criteria decision analysis. Several methodologies exist in the literature for multi-criteria decision making (MCDM), sometimes referred to as multi-criteria decision aiding or multi-criteria decision analysis (MCDA). We use the acronym MCDM/A to consider both.

MCDM/A methods have been used extensively for decision support in many different contexts including construction project risk evaluation, consumer decisions, energy contract risk and water supply risk to name a few (Wang et al., 2018; Wang et al., 2019a, 2019b; Wang et al., 2018; Nie et al., 2018). A recent review of the application of MCDM/A in risk management has shown a significant increase in publications in this decade (de Almeida et al., 2017). The review revealed that the most promising areas of future research for MCDM/A in the risk context are towards improving the managerial decision-making process. The authors conclude that a multi-dimensional view, taking the decision-maker's preferences into account, is necessary to improve decision making for complex problems. This conclusion is of importance when

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Fig. 1. Risk management framework.

considering the application of risk assessments in the asset management context.

A few researchers have proposed frameworks for asset management decisions taking into consideration multiple criteria and decision-maker preferences. Nordgard and Catrinu (2011) applied MCDM/A to select asset management strategies for an electricity distribution system. The method considered a qualitative safety risk criterion as well as maintenance and investment costs as quantitative criteria. Tolerability of safety risk was also considered using a risk matrix. A similar qualitative approach was taken by Lindhe et al. (2013) for MCDM/A for water safety measures. Quantitative risk measures and how to incorporate them in MCDM/A in the asset management context are not discussed by the above authors. Ype Wijnia's PhD thesis, perhaps one of the most comprehensive works considering risk in the asset management context, evaluates risk using a semi-quantitative risk matrix approach (Wijnia, 2016). D. E. Nordgard (2012) discussed the potential application of quantitative risk analysis in asset management decisions, drawing connections between the risk management process and the needs of asset management. However, the author does not propose a methodology for risk-informed cost-benefit analysis for the selection of risk treatment options. de Almeida et al. (2015) present a quantitative and multi-dimensional risk prioritization approach based on multi-attribute utility theory. However, the method does not integrate cost-benefit analysis in the decision process. Bharadwaj, Silberschmidt and Wintle (2012) integrate quantitative risk analysis with discounted cash flow analysis to optimize asset repair/replace decisions, though they do not incorporate multi-dimensional risk measures or decision-maker preferences. Review of the literature shows a gap in the MCDM/A literature for risk and asset management. We see a need for a unified framework through which quantitative and multi-dimensional risk can be evaluated against tolerability criteria and trade-off decisions can be made between risk treatment options, whilst taking into consideration decision-maker preferences.

In this work we present a method for risk-informed decision making in the physical asset management context whereby risk evaluation and cost-benefit analysis are considered in a common framework. The methodology uses quantitative risk measures to prioritize projects based on a combination of risk tolerance criteria, cost-benefit analysis and uncertainty reduction metrics. This paper focuses on the details of the methodology. A simple test case is presented to demonstrate the applicability of the technique, which shows logical consistency in the result. The paper is organized as follows: Section 2 provides an overview of the theoretical background on risk and risk management. Section 3 presents the details of the proposed decision-making framework. In Section 4 we apply the proposed methodology to and illustrate its usefulness through a numerical example. Finally, in Section 5 we summarize the main findings and discuss potential future work.

2. Background

2.1. Defining risk

The word risk has many meanings depending on the context. In the world of finance, risk is defined as the variance in return of an investment (Markowitz, 1952). In the business context, risk is defined as the (negative) variation in performance metrics such as revenue and cost (March and Shapira, 1987). Where public safety is the concern, risk is defined as a measure of the frequency and severity of life-threatening events (CSChE, 2004). The international standard for risk management defines risk as the effect of uncertainty on objectives (International Standards Organization, 2018).

Indeed, the discipline of risk analysis has struggled with defining risk. In a talk given at the 1996 Annual Meeting of the Society for Risk Analysis, the famous risk analysis researcher Stan Kaplan said, "The words of risk analysis have been, and continue to be a problem. Many of you here remember that when our Society for Risk Analysis was brand new, one of the first things it did was to establish a committee to define the word 'risk'. This committee labored for 4 years and then gave up, saying in its final report, that maybe it's better not to define risk. Let each author define it in his own way, only please each should explain clearly what way that is" (S. Kaplan, 1997).

Kaplan and John Garrick (1981) defined risk by first considering the questions that we attempt to answer through risk analysis:

- What can go wrong (i.e. an undesired event)?
- How likely is it that the event may happen?
- If the event does happen, what are the consequences?

A risk can then be defined as the "set of triplets" denoted by $s_i, p(l_i), p(x_i)$ where s_i is the i^{th} scenario, for which l_i denotes the likelihood of the scenario occurrence (given as a frequency, say per annum) and x_i the consequence(s) if the i^{th} scenario occurs. Furthermore, since the complete definition of risk requires a measure of the uncertainty about l_i and x_i, the quantities are defined using probability distributions. As such, we use the notation $p(l_i)$ and $p(x_i)$, where $p(\cdot)$ denotes the probability density functions of the quantities.

The risk triplet as defined by Kaplan and Garrick becomes the basis for two of the core elements of risk management: the identification of scenarios (henceforth referred to as undesired events), and the quantification of the likelihood and consequence(s) along with uncertainty about the quantities (i.e. the risk analysis). We adopt the Kaplan and Garrick definition of risk in this work and demonstrate its usefulness in multi-criteria decision-making under uncertainty for physical asset management.

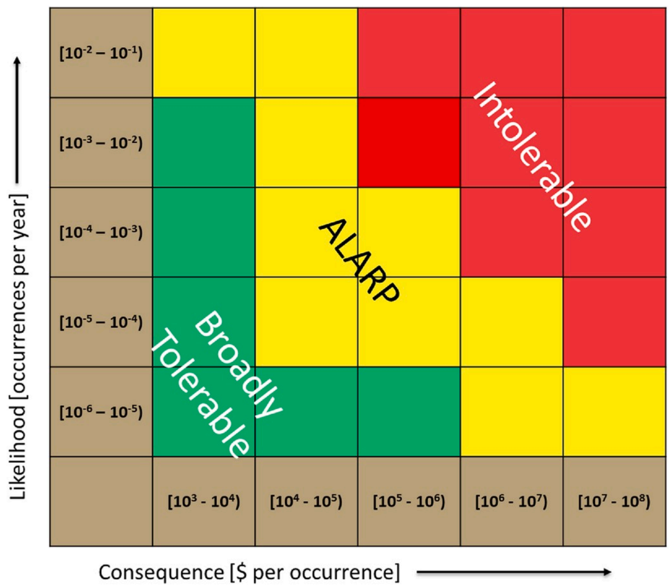


Fig. 2. Example risk matrix.

2.2. Risk management

Risk management is the coordinated set of activities within an organization with the aim towards controlling risk (International Standards Organization, 2018). It is a continuous management process by which risk is identified, analyzed and evaluated. Risk management also involves decision-making with regards to the implementation of risk treatment (Rausand, 2011). The core elements of risk management as defined in ISO 31000 are shown in Fig. 1.

The first step in performing a risk assessment is identifying the undesired events that can cause a negative impact on a part or entirety of a system. This is often called risk or hazard identification. Once undesired events have been identified the next step in risk assessment is determining the likelihood and consequence(s) of these events. The objective of a likelihood analysis is to obtain a measure of the frequency (say per annum) of an undesired event occurring. The objective of a consequence analysis is to obtain a measure of the potential loss incurred as a result of an undesired event (Rausand, 2011).

The final step in a risk assessment is evaluating the risk measure against risk tolerance criteria (Rausand, 2011). A risk matrix is a commonly used method for evaluating risk in an objective way. A risk matrix is used to evaluate the risk of a single scenario, and is constructed by defining levels of likelihood along a row (or column) and levels of consequence along a column (or row). Each cell in the matrix, defined by a row-column pair (i.e. a likelihood and consequence pair) has an associated tolerability, which guides a decision maker by defining the urgency of risk treatment (Cox, 2008). An example risk matrix is shown in Fig. 2, with the following categories:

- Intolerable; risk requires immediate treatment
- ALARP; risk must be As Low as Reasonably Practicable (ALARP, further discussed in Section 3)
- Broadly Tolerable; risk treatment may be undertaken but not required

The results of a risk assessment are used to guide decision-making with respect to risk treatment. Treatment can take many forms (see Fig. 1) and treatment options are not necessarily mutually exclusive. Treatment can include reducing the likelihood of the undesired event (prevention), reducing the consequence(s) (mitigation) or sharing the risk through insurance (transfer). Extreme treatments may include avoiding the risk altogether by removing the source of risk (International Standards Organization, 2018).

In this work we present a method for evaluating risk taking into consideration the uncertainty in the likelihood and consequence(s), verifying the economic viability of a risk treatment option, and finally prioritizing a portfolio of risk treatment options using multi-criteria decision analysis. The method is illustrated using a numerical example.

3. Methodology

This section presents our proposed methodology for risk-informed decision-making for the management of physical assets. The proposed decision-making framework is summarized in the flowchart shown in Fig. 3. The first two steps encompass the risk assessment, whereby risk is identified, quantified and evaluated against tolerance criteria (see Section 3.1). Risk is quantified along three dimensions: life loss, production loss and property loss. Risks requiring treatment as determined by the risk tolerance criteria are identified for risk treatment consideration. Section 3.2 discusses steps three through five in Fig. 3; quantification of risk reduction benefits, cost-benefit analysis of the treatment options, and lastly prioritization of the treatment options using multi-criteria decision analysis. The benefit of a risk treatment option is captured using the present value of the annual risk reduction for each dimension (life, production, property), which is compared against the cost of the treatment option to determine the net present value of the treatment. For prioritization purposes, we capture a decision-maker's preference using weights for risk reduction in each dimension.

3.1. Risk assessment

3.1.1. Identification and analysis

The risk triplet as defined by Kaplan and John Garrick (1981) is often conceptualized using a bowtie analysis, as shown in Fig. 4 (Rausand, 2011). The left side of the bowtie represents the likelihood analysis. The objective of the likelihood analysis is to quantify the frequency (per unit time) of the undesired event (e.g. pipe rupture, compressor failure). The quantification considers the frequency with which various threats can present themselves as well as the barriers (vertical bars) in place to prevent those threats from causing the undesired event. The right side of the bowtie represents the consequence analysis, which consists of two parts: outcome analysis and impact analysis. The outcome analysis considers the many ways in which the undesired event can escalate or de-escalate (e.g. gas release leading to fire and explosion). Mitigating measures (vertical bars) designed to protect against certain outcomes are also considered (e.g. emergency shutdown system preventing a gas leak from escalating). The objective is to quantify the likelihood of various outcomes derived from the likelihood of the undesired event. The impact analysis aims to quantify the end consequences of each outcome (e.g. loss of life, production disruption, property damage, etc.). Note that impacts can vary in severity depending on the outcome (as shown in Fig. 4).

Prior to quantifying a given risk, it is useful to conduct a risk identification exercise with stakeholders. Risk identification can be done in numerous ways depending on the context and the type of risk. As such, we do not dedicate much discussion to this topic, instead directing the reader to Marvin Rausand's book for a thorough review of risk identification methods (Rausand, 2011). We focus on the qualitative output from a risk identification exercise necessary to support quantitative risk analysis; identification and interaction of threats and preventive barriers, identification of mitigation measures and potential outcomes of the undesired event, and the description of potential impacts associated with each outcome. The qualitative output of a risk identification exercise serves as a roadmap for quantitative risk analysis.

Quantitative risk analysis is a complex undertaking, and the methods used can be very context and risk specific. Common methods of likelihood analysis include fault tree analysis, Bayesian belief networks and Petri nets among many others. Such methods are used to model the

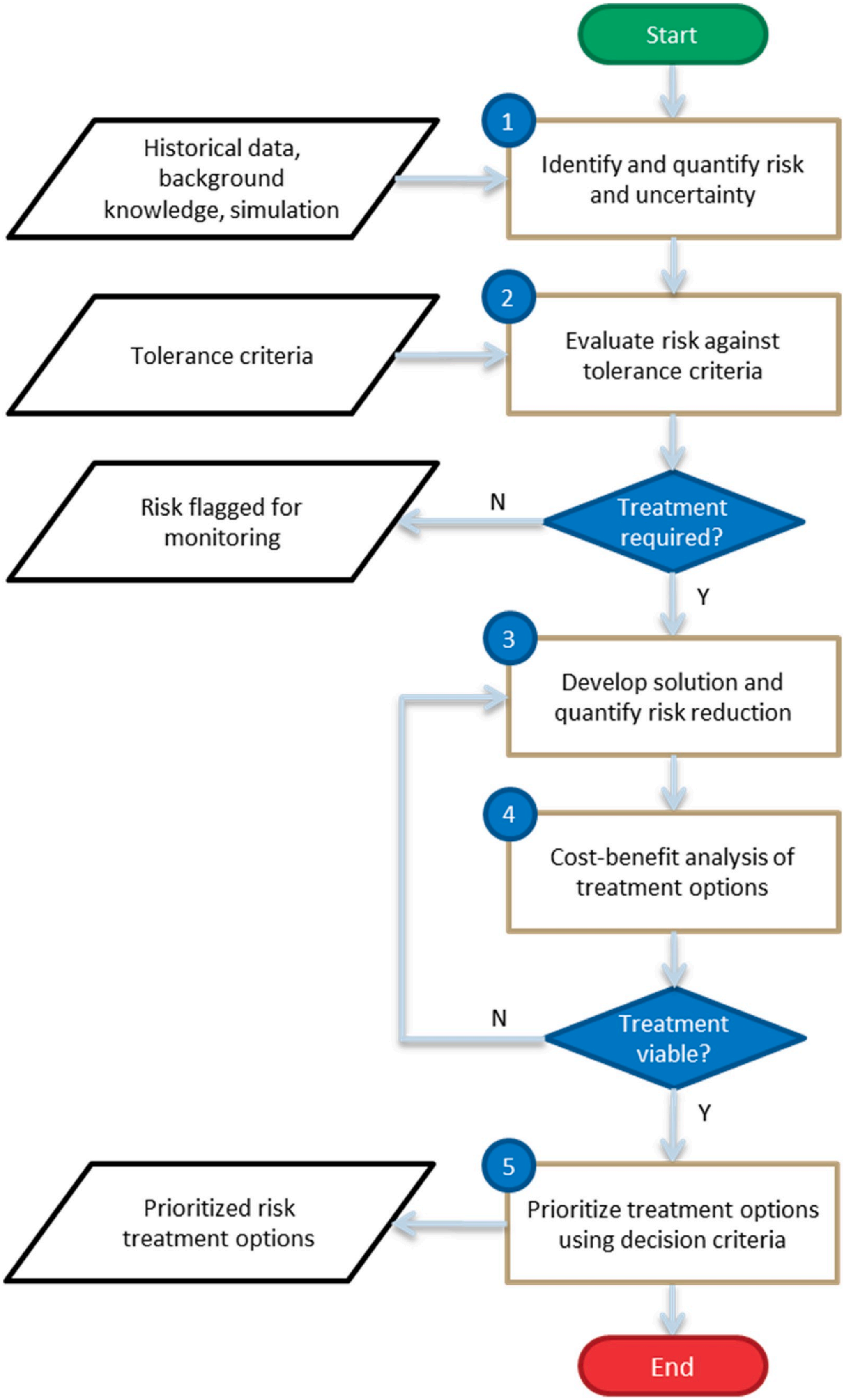


Fig. 3. Decision making flow chart.

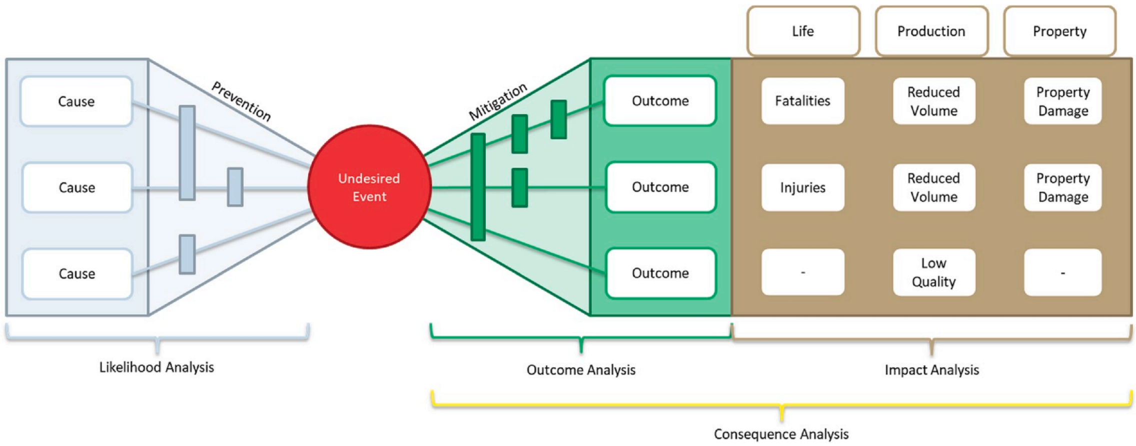


Fig. 4. Bowtie analysis schematic.

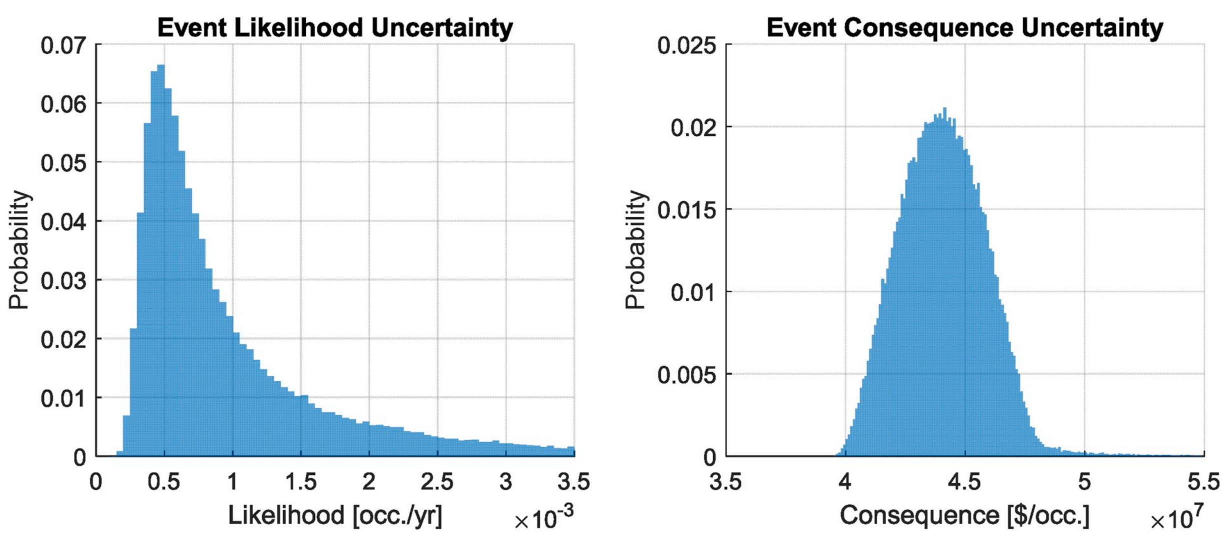


Fig. 5. Example risk uncertainty.

causal relationship between the undesired event and potential root causes. The outcome analysis (see Fig. 4) is almost universally represented (though not always quantified) by means of an event tree analysis. Event tree analysis is used to calculate the frequency of various outcomes after a single initiating event (i.e. the undesired event). The process starts by identifying an initiating event (e.g. gas leak) and its frequency. A sequence of events that can follow the undesired event (e.g. ignition, emergency shutdown failure) are identified and each represents a split in the event tree. This process is repeated until all possible outcomes are identified (Bentley, 1999). Rausand (2011) provides a thorough review of fault trees, event trees and Bayesian networks, as well as other similar techniques. It should be noted that the inputs to fault trees and event trees are often obtained from other context specific analysis techniques. Below are some examples in the context of physical

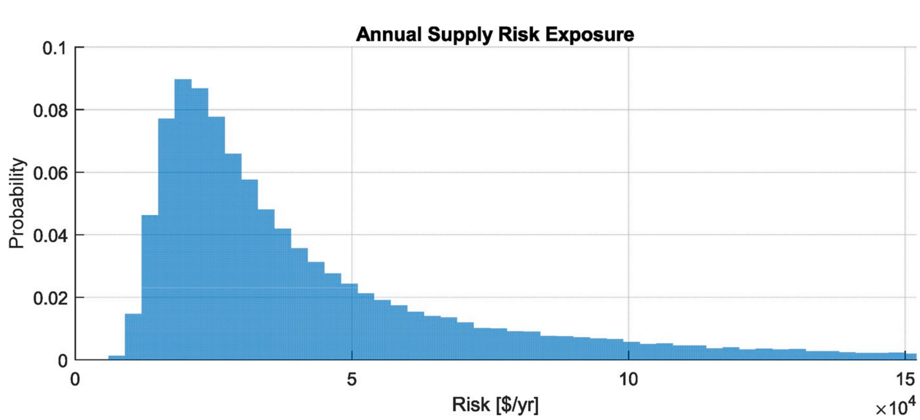


Fig. 6. Example risk quantification.

asset management:

- Mechanical integrity failure prediction of assets through corrosion modeling (Nesic, 2007)
- Reliability analysis of complex asset systems through simulation (Rao and Naikan, 2016)
- Estimated maximum loss models for property damage due to fires and explosions (Gustavsson et al., 2010)
- Resilience modeling of energy infrastructure systems (Wang et al., 2019a, 2019b)

Regardless of the modeling approach used, the important aspect of any quantitative risk analysis is that it provides a full picture of the risk. The complete picture, as described by Kaplan and John Garrick (1981) requires that likelihood and consequence be quantified using probability distributions (see Section 2.1). Decades of experience by risk practitioners, applying sophisticated modeling techniques, has demonstrated that risk simply cannot be adequately represented using expected values of likelihoods and consequences (Aven, 2011). Uncertainty is a core component of risk, particularly when assessing rare and extreme events. We illustrate the Kaplan and Garrick concept of quantitative risk using an example (Fig. 5 and Fig. 6) discussed below.

Consider a gas leak event in an oil and gas production facility. Quantitative analysis of the likelihood suggests that the frequency of occurrence per annum is 1E-3 (or once per 1000 years). Of course, a gas production facility is not expected to be in operation for anything close to 1000 years. Our frequency estimation is simply a reflection of the rarity of the event. If we were able to run an experiment for a year, with 1000 identical facilities, we could expect that one of them would experience a gas leak event. Since such an experiment is infeasible, the frequency of event occurrence is based on other sources of information (or background knowledge) and may be interpreted as a subjective probability of the event occurring (Aven, 2011). Since this background knowledge may be poor or incomplete, it is prudent to represent the uncertainty about our frequency estimation using a probability distribution (Fig. 5, left). The consequence of the gas leak event is also uncertain, as it depends on a number of factors such as the size of the gas leak, the system operating pressure at the time of the leak, whether or not the emergency shutdown system malfunctions, whether or not the gas cloud finds an ignition source, etc. There is uncertainty about all these conditions, and so the consequence is also represented using a probability distribution as shown in Fig. 5 (right). The consequence considered in this case is the cost associated with production loss at the facility and is measured in dollars lost per event occurrence.

Fig. 6 depicts the risk quantification approach used in this work, sometimes referred to as the risk-cost per year (Hastings, 2015). We represent risk as the product of the annual frequency of the undesired event and the financial cost of the consequence(s) if the event occurs. The quantitative measure of risk (R) is therefore the product distribution of the likelihood and consequence distributions ($p(R_i) = p(l_i) \times p(x_i)$). Note that this measure assumes that the two quantities (likelihood and consequence) are independent.

3.1.2. Evaluation

The risk evaluation step requires the decision maker to compare the quantitative measure of risk against tolerability criteria to make a judgement call about whether risk treatment is required. In this section we define risk matrices to support decision-making about the tolerability of risk across three consequence categories in the context of physical asset management; loss of life, loss of production and property loss. We limit the analysis to three consequence categories, though any number may be used depending on the asset management needs. In developing the risk matrices we use a common scale (i.e. dollars) for all consequences to facilitate comparison across the many types of risk in the scope of physical asset management. Loss of production and property loss may be objectively calculated in dollars lost per undesired event

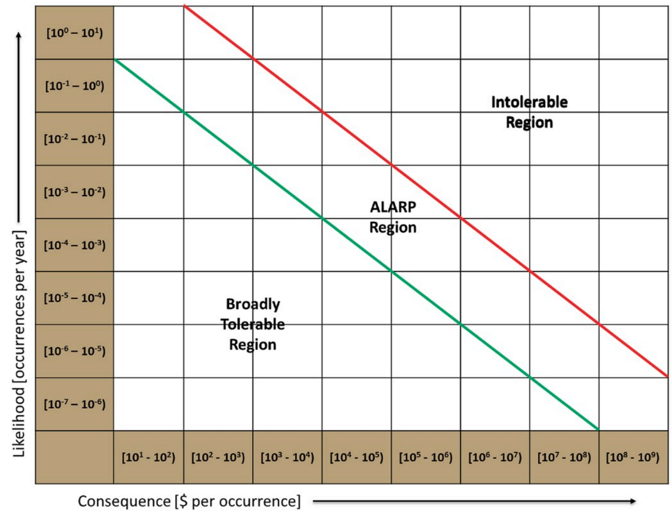


Fig. 7. Suggested risk matrix for loss of life in physical asset management.

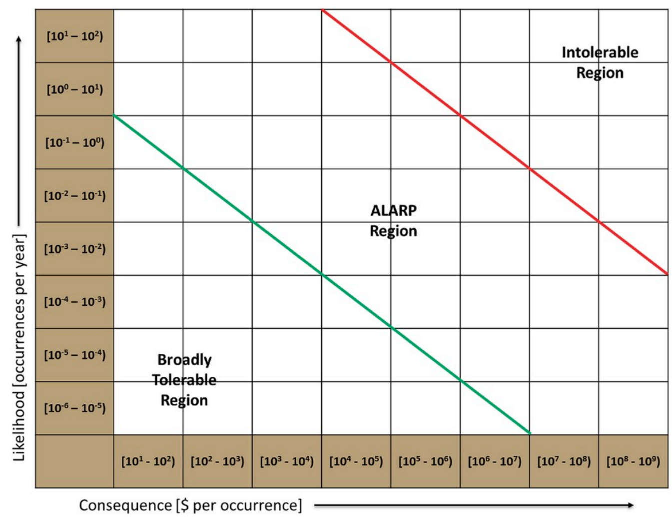


Fig. 8. Suggested risk matrix for financial loss in physical asset management.

occurrence. Production loss being the revenue generating potential of the product (e.g. natural gas supply), and property loss measured by the cost of repairing any damage resulting from the undesired event (e.g. fire damage to equipment). Loss of life is substantially more difficult to quantify in terms of dollars and deserves special consideration.

Converting loss of life to dollars is done using the value of a statistical life (VSL), which is a measure used to perform cost-benefit analysis for public policy decisions. We use the United States government Environmental Protection Agency benchmark value of $10 million in this work (Environmental Protection Agency, 2015). It is important to note that VSL is not meant to reflect the compensation one is willing to accept in exchange for the certainty of one's death as no amount would be considered acceptable. Rather the VSL reflects the amount a decision-maker is willing to spend to prevent a potential fatality (Aven, 2011). Risk in the asset management context may require a measure of loss of life where the consequence is an injury rather than a fatality (Wijnia, 2016). An objective measure is needed to scale the VSL of $10 million per fatality to injury levels. A reputable source for such scaling is the World Health Organization's (WHO) methods and data sources for global burden of disease estimates (World Health Organization, 2017). The WHO has derived disability weights for a wide range of diseases and injuries that reflect the relative severity as compared to mortality, where

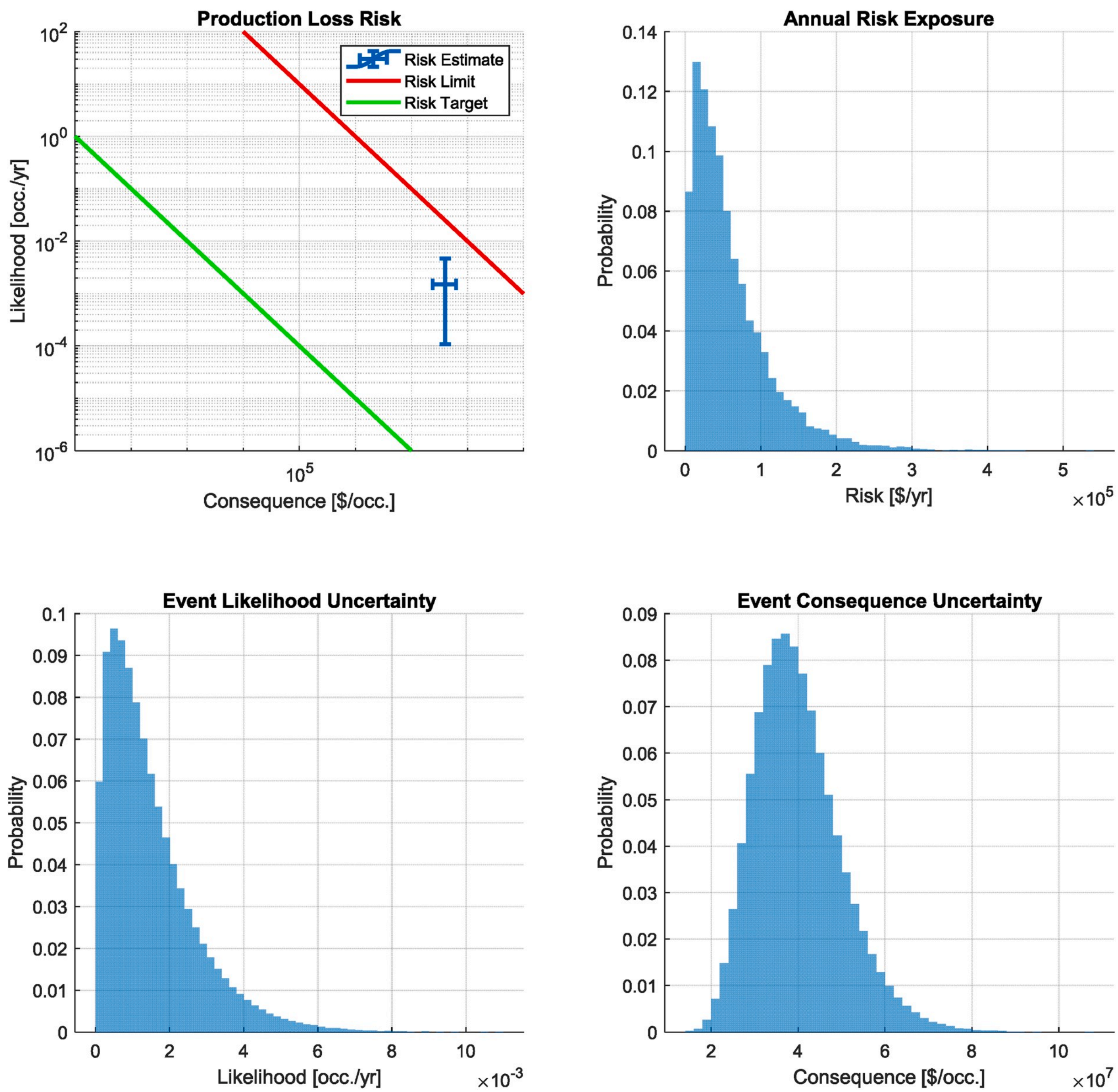


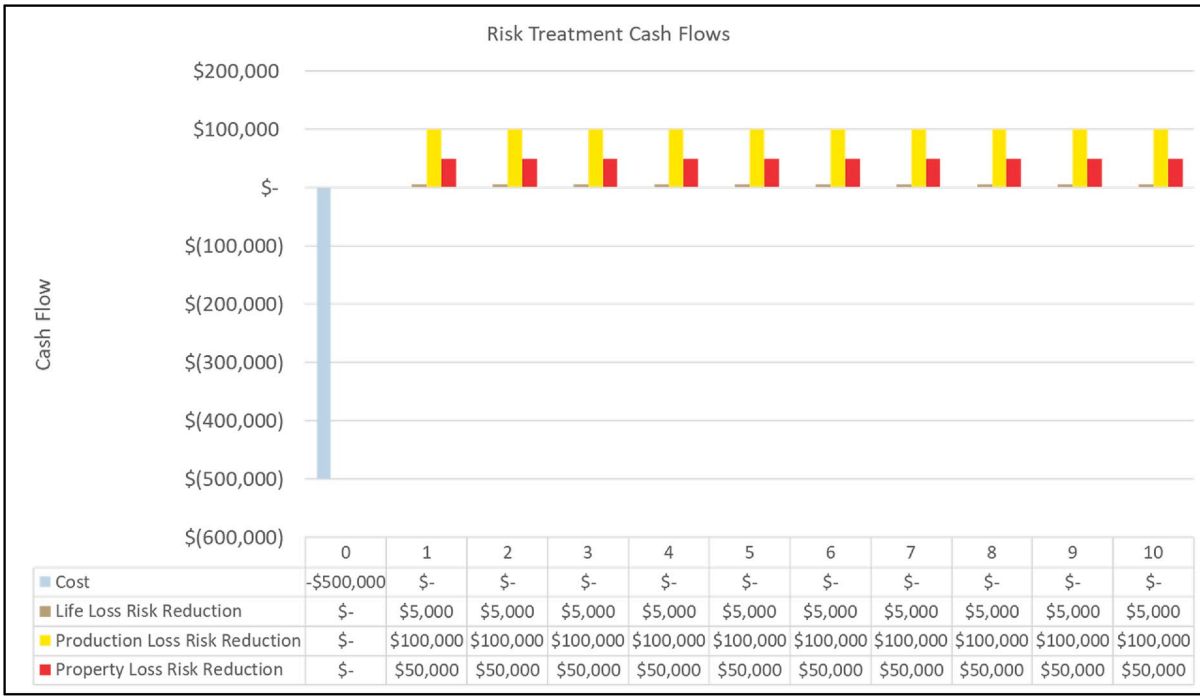
Fig. 9. Example risk evaluation dashboard.

disability weight of 1 is equivalent to death and 0 reflects perfect health. Using the WHO disability weights, one can objectively scale a VSL to arrive at dollar equivalents for injuries. It is beyond the scope of this paper to present such analyses. However, in this work we use $1 million as a benchmark for a long-term injury in developing the risk matrix.

Fig. 7 and Fig. 8 show the risk matrices developed in this work for application in physical asset management decision making. The matrices span eight orders of magnitude for both consequence and likelihood. The eight orders of magnitude were chosen to cover the many types of risk-informed decisions required for asset management. For example, an engineered system may experience component failures that are high frequency and low consequence. On the other hand, assets within the system may be susceptible to extreme events (low frequency, high consequence). For showing the risk criteria on the matrix we do not use colour-coded cells, which hamper typical risk matrices by causing incorrect prioritization of risks (Cox, 2008). Instead we divide the matrices into regions of intolerable, ALARP and broadly tolerable (see Section 2.2) using the concept of a risk limit and risk target.

The United Kingdom's Health and Safety Executive (UK HSE) published a risk-based decision-making process in which a loss of life risk limit for a member of the public is defined as an annual probability (chance) of one in ten thousand. The UK HSE defined the risk target at one in a million chance of fatality per annum (UK Health and Safety Executive, 2001). The UK HSE limit and target and the previously defined VSL of $10 million provide an anchor point for the risk limit and target (Fig. 7). At a consequence level of $10 million (i.e. a single fatality), a likelihood equal to or less than 10^{-6} occurrences per year is broadly tolerable. Similarly, at a consequence level of $10 million, a likelihood equal to or greater than 10^{-4} occurrences per year is intolerable. Now considering a neutral attitude towards increasing and decreasing risk, we create the risk limit and target lines. For example, for a lower consequence of $1 million, we would set any likelihood of occurrence greater than or equal to 10^{-3} as intolerable. In other words, for an order of magnitude lower consequence we accept an order of magnitude higher likelihood.

Risk limits and targets for financial consequences are more company specific than loss of life. A possible approach is to consider a company's annual average historical (or forecasted) net earnings for a length of time equal to the asset management planning horizon. The annual consequence limit can be then set considering a percentage of the



	0	1	2	3	4	5	6	7	8	9	10
Cost	-$500,000	$-	$-	$-	$-	$-	$-	$-	$-	$-	$-
Life Loss Risk Reduction	$-	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Production Loss Risk Reduction	$-	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000
Property Loss Risk Reduction	$-	$50,000	$50,000	$50,000	$50,000	$50,000	$50,000	$50,000	$50,000	$50,000	$50,000

Fig. 10. Example of risk reductions as cash flows.

average annual net earnings based on the amount the company can absorb given its financial position. A target is somewhat easier to set since a company should always consider a cost-benefit approach when it comes to potential financial losses. As such, we set the target as $10 annual risk exposure in Fig. 8.

Risk matrices have been criticized in the literature, with the primary argument being that they fail to prioritize risks and therefore are not effective decision making tools (Cox, 2008; Wijnia, 2016). Nevertheless, risk matrices have proven to be so effective in risk communication, even with stakeholders with little or no risk management knowledge, that they continue to see widespread use in both academia and industry. In fact, it appears that much of the criticism of risk matrices is rooted in improper application rather than the method itself (Alp, 2006). In this work we take the perspective that risk and risk criteria are nothing more than reference points to inform asset management decisions (Aven, 2011). As such, risk matrices should not be used in a mechanistic decision procedure about the tolerability or intolerability of risk. With this in mind, we augment the risk matrix with additional information about the risk in question, providing a more honest and open picture of the risk, which better supports risk-informed decision-making.

An example risk evaluation dashboard is shown in Fig. 9. The top left chart plots the likelihood of an undesired event and associated consequence(s) on a risk matrix along with the 95% prediction intervals for each measure. The top right chart shows the annual risk exposure as the product distribution of the likelihood distribution (bottom left) and consequence distribution (bottom right).

Representation of the uncertainty ranges as well as distributions for likelihood, consequence and annual risk exposure give the decision-maker a complete picture of the risk. In this way, the decision-maker can use the risk matrix effectively as a visual aid in examining the tolerability of the risk. Evaluation of risk tolerability is not limited to expected values of likelihood and consequence. Instead, the decision-maker may consider the optimistic and pessimistic percentiles and evaluate tolerability based on probability of exceedance of risk limit or target thresholds as defined by the risk matrix.

3.1.3. First decision: treatment urgency

Upon completion of Steps 1 and 2 in Fig. 3, we reach the first decision point, where a decision-maker must determine the urgency of treatment for the risk in question. If a risk is in the intolerable or ALARP region of the risk matrix, the decision-maker will consider risk treatment options. If the decision-maker has perfect information, then an intolerable risk implies that risk treatment is mandatory, while a risk in the ALARP region is treated if the risk reduction benefits outweigh the treatment costs. Of course, the judgement about whether a risk is intolerable, ALARP or broadly tolerable is often difficult in practice due to the uncertainty in both the likelihood and consequence of a risk. There is a recognition now among stakeholders that risk evaluations must go beyond expected values and take into consideration the uncertainty of the risk estimate (Aven, 2010). As such, we recommend that the decision-maker use the probability of exceedance of the risk limit to determine whether risk treatment is mandatory. Based on the risk matrices defined in Figs. 7 and 8, the annual risk exposure limit for loss of life is $1000 per year and the limit for financial loss is $1 million per year. The exceedance probability threshold to use is a judgment to be made by the decision-maker that is dependent on his or her aversion to risk. Similarly, the decision-maker may consider the risk treatment in the ALARP region based on the exceedance probability relative to the risk targets as defined by the risk matrix. Once a decision-maker determines whether to proceed with risk treatment, evaluation and prioritization of treatment options is necessary, as will be discussed in the next section.

3.2. Risk treatment

In this section we present a cost-benefit analysis of potential risk treatment options as well as prioritization of the viable options. Cost-benefit analysis (step 3 and 4) and the second decision point (see Fig. 3) are discussed in sub-section 3.2.1. Step 5 in Fig. 3, prioritization of viable treatment options using MCDM/A, is discussed in sub-section 3.2.2.

3.2.1. Cost-benefit analysis

Generally, if a risk falls in the ALARP region of the risk matrix (Figs. 7 and 8), the decision-maker should perform some form of cost-benefit analysis to determine if a risk treatment option is viable. Whilst treatment of risks in the intolerable region of the risk matrix is considered mandatory, it may be prudent to perform similar cost-benefit analyses, particularly if the risk treatment options are costly. Furthermore, a risk in the broadly tolerable region does not preclude treatment. As discussed in Section 3.1, there may be significant uncertainty in a risk analysis. Therefore, a decision-maker may choose to treat a risk by virtue of the precautionary principle, even if the expected values of the likelihood and consequence(s) places the risk in the broadly tolerable region of the risk matrix (Aven, 2011). Considering the discussion above, it would be prudent to perform a cost-benefit analysis of a risk treatment option regardless of the tolerability of the risk being addressed.

For physical asset management, the preferred method of performing cost-benefit analysis is by computing the net present value (NPV) of the treatment option (Hastings, 2015). All costs of the treatment option, including design and commission as well as ongoing running costs must be considered. The risk reduction (dR), calculated as the difference in the expected values of the pre and post-project annual risk exposure ($dR = E(R_{pre}) - E(R_{post})$), can be treated as a cash flow back to the company. Fig. 10 illustrates the concept where a capital outlay of $500, 000 provides a company with annual risk reductions, treated as positive cash flows, for a 10-year period.

We calculate the NPV as shown by Equation (1) to determine the viability of a risk treatment option. The NPV is the total risk reduction afforded by the treatment minus costs to implement and maintain/run the treatment option. A positive NPV implies that the risk reduction benefit outweighs the cost of the treatment option.

$$\begin{aligned} NPV = & (Expected\ present\ value\ of\ loss\ of\ life\ risk\ reduction) \\ & +(Expected\ present\ value\ of\ loss\ of\ production\ risk\ reduction) \\ & +(Expected\ present\ value\ of\ loss\ of\ property\ risk\ reduction) \\ & -(Expected\ present\ value\ of\ cost\ of\ risk\ treatment\ option). \end{aligned} \tag{1}$$

In the simplest case, one can consider the risk reduction benefit and the risk treatment running costs as constant annual cash flows. In such a scenario, the present values of the cash flows can be calculated using the discounting factor for an annuity as shown in Equation (2) (Fraser et al., 2000).

$$\begin{aligned} NPV = & dR_{life} \times \left[\frac{1-(1+r)^{-n}}{r}\right] + dR_{prod} \times \left[\frac{1-(1+r)^{-n}}{r}\right] + dR_{prop} \\ & \times \left[\frac{1-(1+r)^{-n}}{r}\right] - C_1 - C_2 \times \left[\frac{1-(1+r)^{-n}}{r}\right], \end{aligned} \tag{2}$$

where dR_{life}, dR_{prod} and dR_{prop} represent the annual risk exposure reductions for loss of life, loss of production and loss of property afforded by the risk treatment option in question. C_1 is the initial capital outlay to implement the treatment option, and C_2 is the ongoing running cost of the treatment. The number of periods (n) is based on the duration for which the risk reduction benefit will be received. If for example, a modification is being made to improve the reliability of a critical asset, the remaining useful life of the asset may be considered as the duration of the risk benefit. For a new asset, such as a new safety system in a production facility, the duration may be the useful life of the safety system or the planned life of the production facility (whichever is shorter). If the risk treatment requires periodic re-investment (e.g. maintenance capital) then the duration of the benefit should be equal to the re-investment period, provided it is shorter than the remaining life of the asset. Lastly, r is the appropriate risk-adjusted discount factor. However, discussion on how the discount factor should be defined is beyond the scope of this paper.

3.2.2. Second decision: treatment viability

Upon completion of step 3 and 4 in Fig. 3, we reach the second decision point, where a decision-maker must determine the viability of the treatment option. Strictly speaking, any treatment with an NPV greater than zero is considered viable. However, considering the uncertainty in risk analysis (and even discounted cash flow analysis), a decision-maker must apply his/her judgement about the required NPV for a treatment option to be considered viable. We have indicated an iterative process at this step in Fig. 3 as a decision-maker may consider modifications to the treatment option if the NPV does not suggest viability. Once a decision-maker determines whether to proceed with risk treatment, prioritization of treatment options is necessary, as will be discussed in the next section.

Table 1
AHP numeric scale with linguistic interpretation.

Intensity of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgement slightly favor one over the other.
5	Much more important	Experience and judgement strongly favor one over the other.
7	Very much more important	Experience and judgement very strongly favor one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

3.2.3. Prioritization

A decision-maker may be faced with multiple project alternatives to treat a single risk or multiple projects to treat many different risks. It is inevitable that in the asset management context, the number of potential projects will be greater than the operating budget can accommodate. As a result, there is a need for an objective method of prioritizing projects while taking into consideration decision-maker preferences and multiple project prioritization criteria. In this section we discuss how MCDM/A may be used to prioritize risk treatment options (i.e. projects or alternatives).

We implement a MCDM/A method known as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Yoon and Hwang, 1995). As the name suggests, the method prioritizes decision alternatives based on the idea that the best solution is one that is the shortest Euclidian distance from the ideal solution and farthest distance from the anti-ideal solution. The only inputs required for the TOPSIS method are weights for each of the decision criteria, and specification about whether a decision criterion must be maximized or minimized for the ideal solution. In the TOPSIS method, the weight for each decision criterion is meant to be reflective of the decision-maker's preferences (e.g. valuing life risk reduction more than property risk reduction). The Analytic Hierarchy Process (AHP) is a natural fit for determination of such weights. AHP is a MCDM/A methodology that has been widely used in both academia and industry (Saaty, 1980). The method breaks the objective (selection of the best alternative) into decision criteria and sub-criteria. The decision-maker performs pairwise comparison of the decision criteria, followed by pairwise comparison of the sub-criteria. The decision-maker expresses his/her preference towards a certain criteria using Saaty's numeric scale shown in Table 1 (Saaty, 1980). The overall weight of each decision criterion is then calculated.

Both AHP and TOPSIS methods have been widely used in the academic literature, and in the risk and asset management contexts (Kabir et al., 2014; de Almeida et al., 2017). Many researchers have used a hybrid approach to MCDM/A by combining AHP and TOPSIS in the way we do in this work (Ak and Gul, 2019; Samvedi et al., 2013; Prakash and Barua, 2015; Zyoud et al., 2016). In the remainder of this section we provide a brief review of the AHP and TOPSIS methods in the context of application in this work. For full details of the methodology, we refer the reader to the many MCDM/A textbooks that discuss these popular methods (Ishizaka and Nemery, 2013).

Suggested decision criteria are shown in Fig. 11, consisting of three

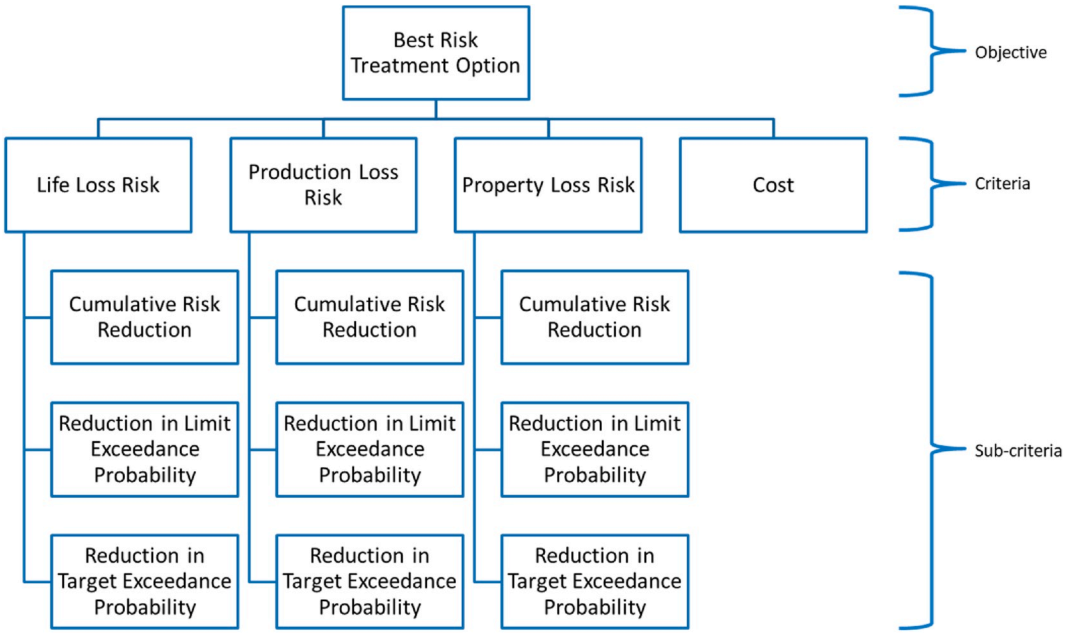


Fig. 11. AHP decision structure.

Table 2
TOPSIS prioritization criteria.

Criteria	Sub-Criteria	Measure	Ideal Solution	Weight
Life Loss Risk	Cumulative Risk Reduction	$PV(\Delta R_{life})$	Maximize	37.3%
	Reduction in Limit Exceedance Probability	$p(R_{life}^{pre} > 1000) - p(R_{life}^{post} > 1000)$	Maximize	15.7%
	Reduction in Target Exceedance Probability	$p(R_{life}^{pre} > 10) - p(R_{life}^{post} > 10)$	Maximize	3.3%
Production Loss Risk	Cumulative Risk Reduction	$PV(\Delta R_{prod})$	Maximize	8.0%
	Reduction in Limit Exceedance Probability	$p(R_{prod}^{pre} > 1mil) - p(R_{prod}^{post} > 1mil)$	Maximize	1.7%
	Reduction in Target Exceedance Probability	$p(R_{prod}^{pre} > 10) - p(R_{prod}^{post} > 10)$	Maximize	0.7%
Property Loss Risk	Cumulative Risk Reduction	$PV(\Delta R_{prop})$	Maximize	8.1%
	Reduction in Limit Exceedance Probability	$p(R_{prop}^{pre} > 1mil) - p(R_{prop}^{post} > 1mil)$	Maximize	1.5%
	Reduction in Target Exceedance Probability	$p(R_{prop}^{pre} > 10) - p(R_{prop}^{post} > 10)$	Maximize	0.7%
Cost	n/a	$PV(Cost)$	Minimize	23%

risk criteria and one cost criteria. The three risk criteria are each evaluated using three sub-criteria: cumulative risk reduction (i.e. the present value of the annual risk exposure reduction), reduction in the probability of exceeding the risk limit, and reduction in the probability of exceeding the risk target. Decision-maker preferences are determined first for the criteria by performing a pairwise comparison and eliciting how much more importance the decision-maker places on one criterion over another. Similarly, pairwise comparison is performed for each group of sub-criteria. The AHP calculation is then performed by constructing the comparison matrices for the criteria and sub-criteria, calculating criteria weights, calculating the sub-criteria weights, and finally the overall weighting of each sub-criteria (Saaty and Vargas, 2012). We have provided the comparison matrices used in this work in the Supplementary Material. Note that the importance should be evaluated conditioned on the risk treatment already determined to be viable from a cost-benefit perspective. The objective now is prioritization of viable alternatives (see step 5 in Fig. 3).

Table 2 provides a summary of the prioritization criteria applied in the TOPSIS method, along with overall weights derived from the AHP pairwise comparison described previously. Cumulative risk reduction measures are calculated as the present value of the annual risk reduction: $PV = dR \times \left[\frac{1-(1+r)^{-n}}{r}\right]$. The present value of costs associated with a risk treatment is similarly calculated. To capture the uncertainty in the risk analysis in our decision-making we consider the change in exceedance probability of the annual risk exposure compared to the risk limit and target (see Section 3.1). Table 2 also indicates whether we want to maximize or minimize a measure for the ideal solution, and vice-versa for the anti-ideal solution. The TOPSIS method may then be applied to prioritize a list of alternatives using objective measures derived from quantitative risk analysis. By deriving the weights through the AHP method described previously, we ensure that the prioritization will be consistent with decision-maker preferences.

A typical TOPSIS decision matrix may be constructed as shown in Table 3, where the performance measure of the ith alternative against the jth criterion is given by x_{ij}. Performance measures are calculated as specified in Table 2.

The performance measures for the decision criteria vary in units and scale. A such we must first normalize the decision matrix using Equation

Table 3
Example TOPSIS decision matrix.

Decision Matrix	Criterion 1	Criterion 2	Criterion 3
Alternative 1	x_{11}	x_{12}	x_{13}
Alternative 2	x_{21}	x_{22}	x_{23}
Alternative 3	x_{31}	x_{32}	x_{33}

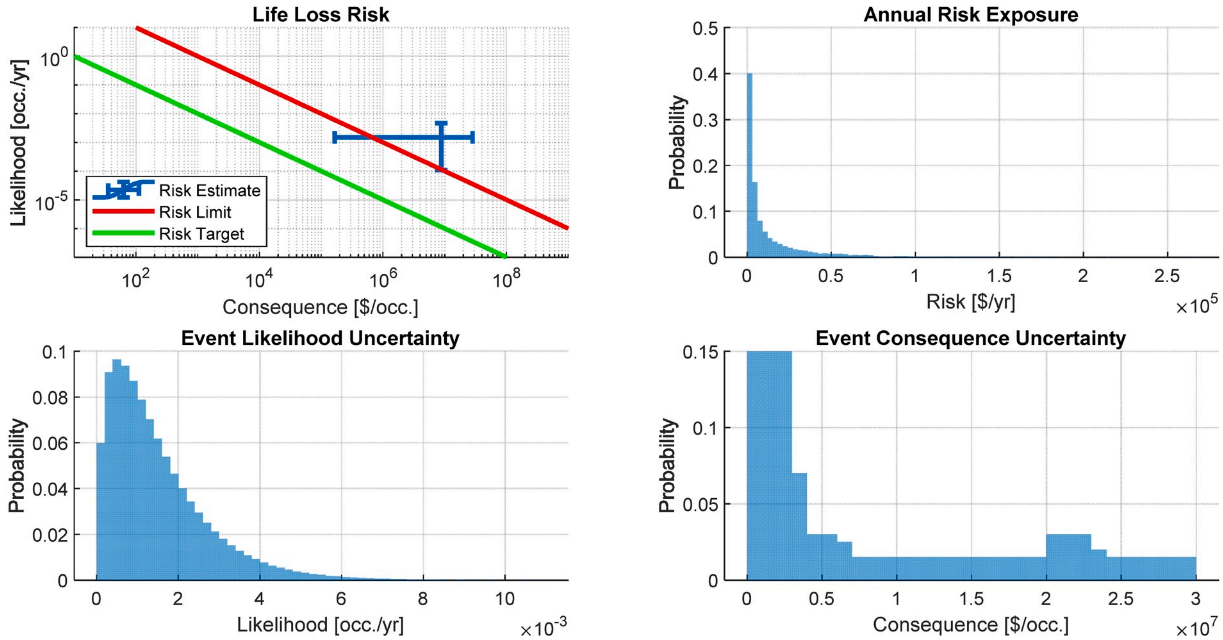


Fig. 12. Gas leak - loss of life - baseline risk results.

(3), where a is the number of alternatives (Ishizaka and Nemery, 2013):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{a} x_{ij}^2}}. \tag{3}$$

A weighted normalized decision matrix is calculated by multiplying each normalized measure with the weight of the criteria ($v_{ij} = w_j \times r_{ij}$) as calculated using the AHP method and given in Table 2. For each criterion we define the ideal as $v_j^+ = max_j(v_{1j}, \ldots, v_{aj})$ and the anti-ideal as $v_j^- = min_j(v_{1j}, \ldots, v_{aj})$ if the criterion is to be maximized. Conversely, if the criterion is to be minimized, the ideal and anti-ideal are defined as $v_j^+ = min_j(v_{1j}, \ldots, v_{aj})$ and $v_j^- = max_j(v_{1j}, \ldots, v_{aj})$. The distance of each alternative from the ideal (d_i^+) and anti-ideal (d_i^-) is calculated using Equation (4) (Ishizaka and Nemery, 2013).

$$d_i^+ = \sqrt{\sum_{j=1}^{c}\left(v_j^+ - v_{ij}\right)^2} \text{ and } d_i^- = \sqrt{\sum_{j=1}^{c}\left(v_j^- - v_{ij}\right)^2} \tag{4}$$

Finally, the closeness coefficient of each alternative is calculated as $C_i = d_i^- / (d_i^+ + d_i^-)$. The closeness coefficient approaches one the closer the alternative is to the ideal solution, and zero the closer it is to the anti-ideal. The closeness coefficient is then used to prioritize risk treatment alternatives (Ishizaka and Nemery, 2013).

4. NUMERICAL EXAMPLE

In this section we illustrate the decision-making framework described in Section 3 using a numerical example. In this case we

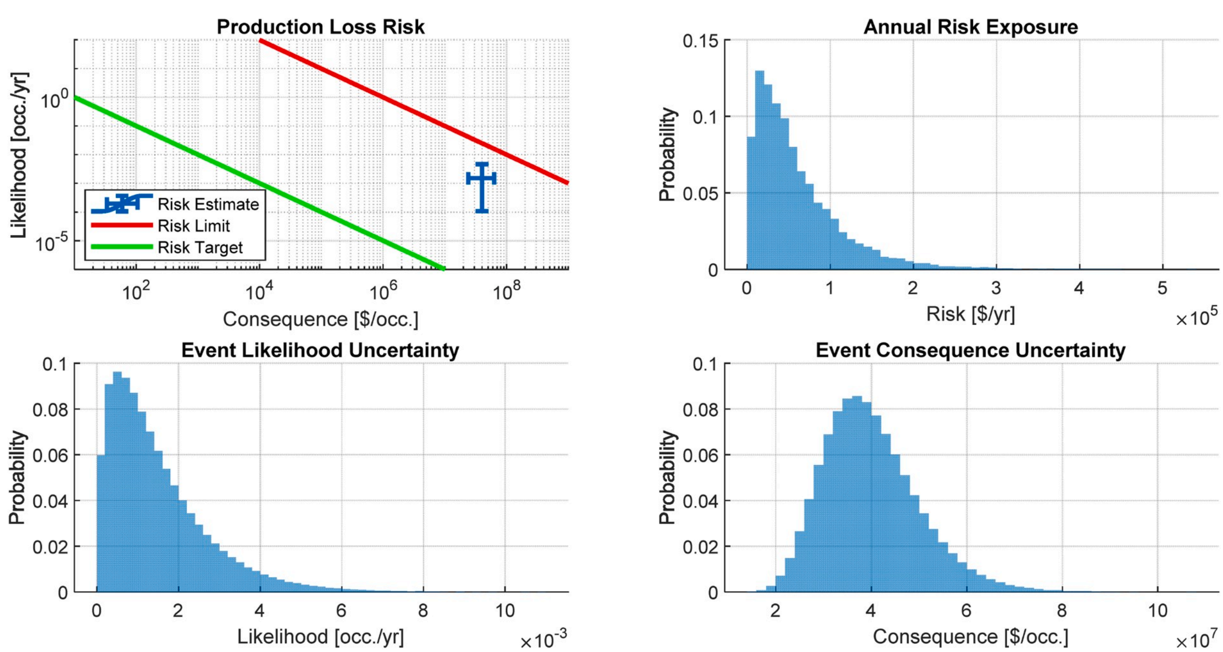


Fig. 13. Gas leak - loss of production - baseline risk results.

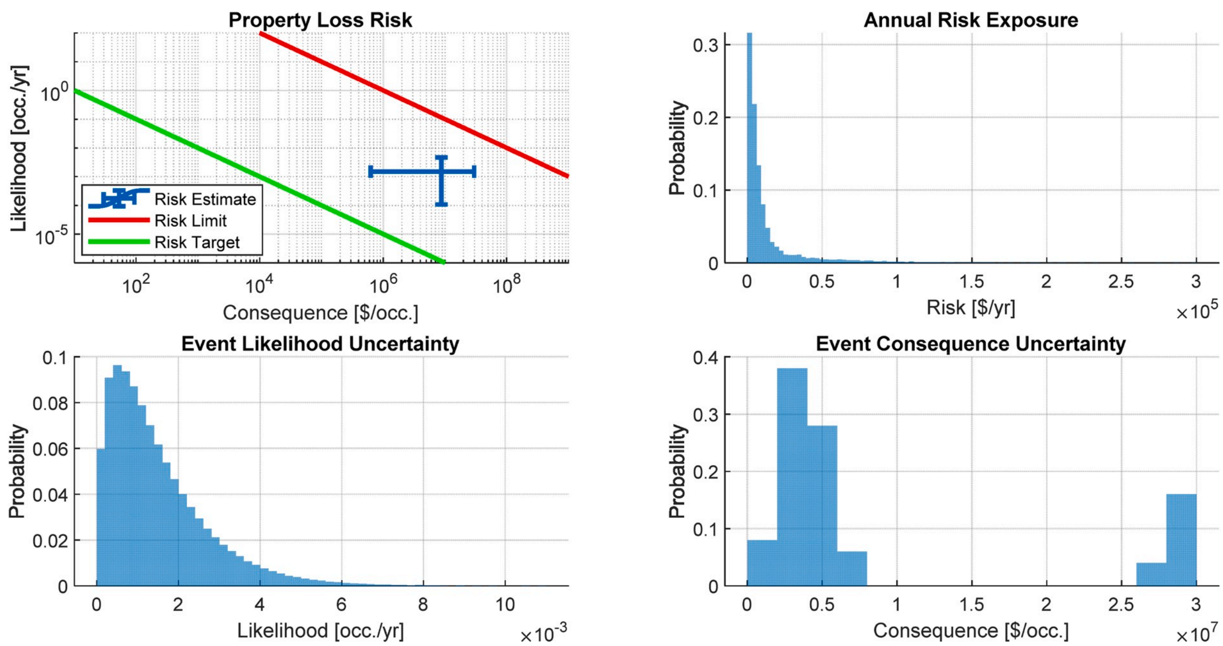


Fig. 14. Gas leak - loss of property - baseline risk results.

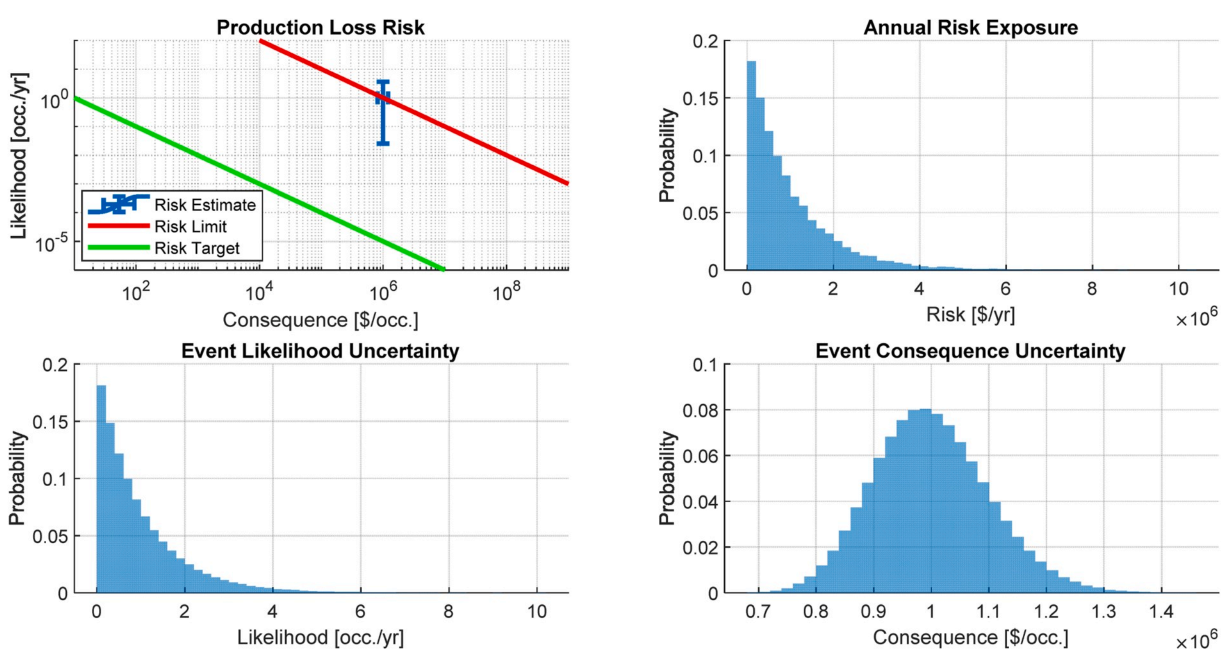


Fig. 15. Compressor failure - loss of production - baseline risk results.

consider a natural gas compression facility for which we must prioritize investments for risk treatment of critical assets. Degradation of high-pressure gas containing pipework within the facility has led to concerns of potential gas leaks in the facility, which has the potential to cause loss of life, property damage and result in significant production interruption. Furthermore, the aging fleet of compressors are experiencing major failures annually (sometimes more) resulting in production interruption. The decision-making process begins by first obtaining a baseline measure of the risk in the facility using quantitative risk analysis. The results are summarized in sub-section 4.1.1. Potential risk treatment options and their effect on the facility risk exposure is discussed in sub-section 4.1.2. We do not discuss the quantification approach in detail as risk analysis methods are not the topic of this paper. The focus is on how the results of a quantitative risk analysis may be used to support decision-making in the physical asset management context, to which end we provide a detailed discussion of risk treatment prioritization in sub-section 4.1.3.

4.1. Baseline results

Fig. 12 through Fig. 14 show the risk results for a potential gas leak event. The likelihood of occurrence was determined through statistical analysis of historical gas leaks within similar facilities. The consequence of the gas leak event was determined analytically by modeling the probability of ignition (Rew and Daycock, 2004), calculating fire and explosion effects distances and resultant personnel vulnerability (CCPS, 2010; CCPS, 2000), and using facility occupancy levels. Production consequence was estimated based on historical throughput of the facility

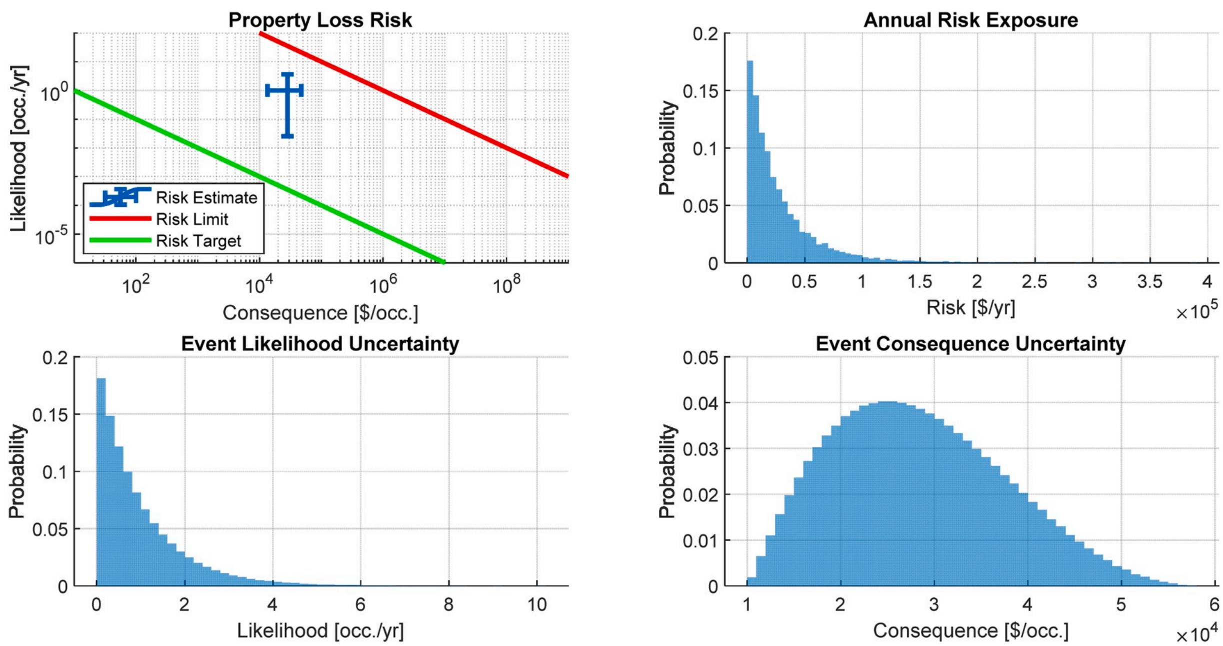


Fig. 16. Compressor failure - loss of property - baseline risk results.

and expert judgment about the duration of the disruption event. Property consequence was analytically derived using the same method for loss of life. However, a fire and gas detection and mitigation system was credited. Fault tree analysis was used to analyze the reliability of the system. Loss of life (Fig. 13) exceeds the $1000 risk limit with a probability of exceedance of 80%. With such a high exceedance probability, the decision-maker may consider risk treatment mandatory. Production loss risk (Fig. 14) and property loss risk (Fig. 15) are in the ALARP region of the risk matrix, meaning risk treatment options will be subject to cost-benefit consideration. Fig. 15 and Fig. 16 show the production loss and property loss risk associated with potential compressor failure events. The likelihood was modeled using a Poisson process, with parameters obtained through statistical analysis of compressor failure data. Production consequence was estimated based on historical throughput of the facility and expert judgment about the duration of the compressor outages. Property consequence was derived from historical data of compressor repair costs. Production loss (Fig. 15) risk exceeds the risk limit with a probability of exceedance of 36.5%. Given the (relatively) low exceedance probability, the decision-maker may require cost-benefit analysis in this case. Property loss risk (Fig. 16) is in the ALARP region. As such, treatment options will require cost-benefit analysis. Risk treatment options are discussed in the next sub-section.

4.1.1. Risk treatments

Potential risk treatments for gas leak events and compressor failures are summarized in Table 4, along with the present value of the cost of the options. The risk reduction benefits of each option are summarized in Table 5. Fig. 17 is a graphical representation of the risk reduction benefit with respect to loss of life afforded by treatment option 1 (automation upgrades). Risk results pre- and post-treatment are plotted on the same charts to demonstrate the benefit. Automation upgrades essentially reduces the occupancy level within the facility. In other words, there is now a lower chance of multiple persons being affected by the gas leak event, resulting in a reduction in the consequence of a gas leak event. The likelihood is not affected. We can then obtain the annual risk reduction by comparing the difference in the expected values of the annual risk exposure. The present value of the risk reduction can be calculated as described in Section 3.2.1. Results in Tables 4 and 5 for the other treatment options were similarly obtained.

Strictly speaking, cost-benefit analysis would eliminate treatment options 2 and 5 due to a negative NPV. Option 5 is eliminated because option 4 reduces the production loss risk due to compressor failure to below the risk limit. However, since treatment option 1 does not reduce the loss of life risk below the limit (see Fig. 17), we consider option 2 for prioritization, discussed in the next section. However, we evaluate the

Table 4
Risk treatment options.

Treatment No.	Name	Description	Risk Addressed	$PV(Cost)$
1	Automation Upgrades	Automation for the facility will reduce the amount of time personnel need to spend within the facility.	Loss of Life due to Gas Leak	$400,000
2	Pipework Replacements	Replacement of aging pipework within the facility.	Loss of Life/Production/Property due to Gas Leak	$10,000,000
3	Fire Suppression System	Installation of a fire suppression system that reduces the potential for extensive damage and extended production outage in the event of a gas leak.	Loss of Production/Property due to Gas Leak	$350,000
4	Compressor Improvements	Reliability improvements that reduce the number of unexpected failures of compressor units.	Loss of Production/Property due to Compressor Failure	$6,000,000
5	Redundant Compressor Unit	A standby compressor unit that can be brought online in the event of a compressor failure.	Loss of Production/Property due to Compressor Failure	$30,000,000

Table 5
Risk treatment benefits summary.

Treatment No.	Life Loss			Production Loss			Property Loss		
	$PV(\Delta R_{life})$	$\Delta p(ExceedLimit)$	$\Delta p(ExceedTarget)$	$PV(\Delta R_{prod})$	$\Delta p(ExceedLimit)$	$\Delta p(ExceedTarget)$	$PV(\Delta R_{prop})$	$\Delta p(ExceedLimit)$	$\Delta p(ExceedTarget)$
1	$360,000	0.46	0.025	0	0	0	0	0	0
2	$36,000	0.33	0.025	$740,000	0	0	$160,000	0	0
3	0	0	0	$290,000	0	0	$68,000	0	0
4	0	0	0	$5,900,000	0.36	0.011	$170,000	0	0
5	0	0	0	$12,400,000	0.36	0	0	0	0

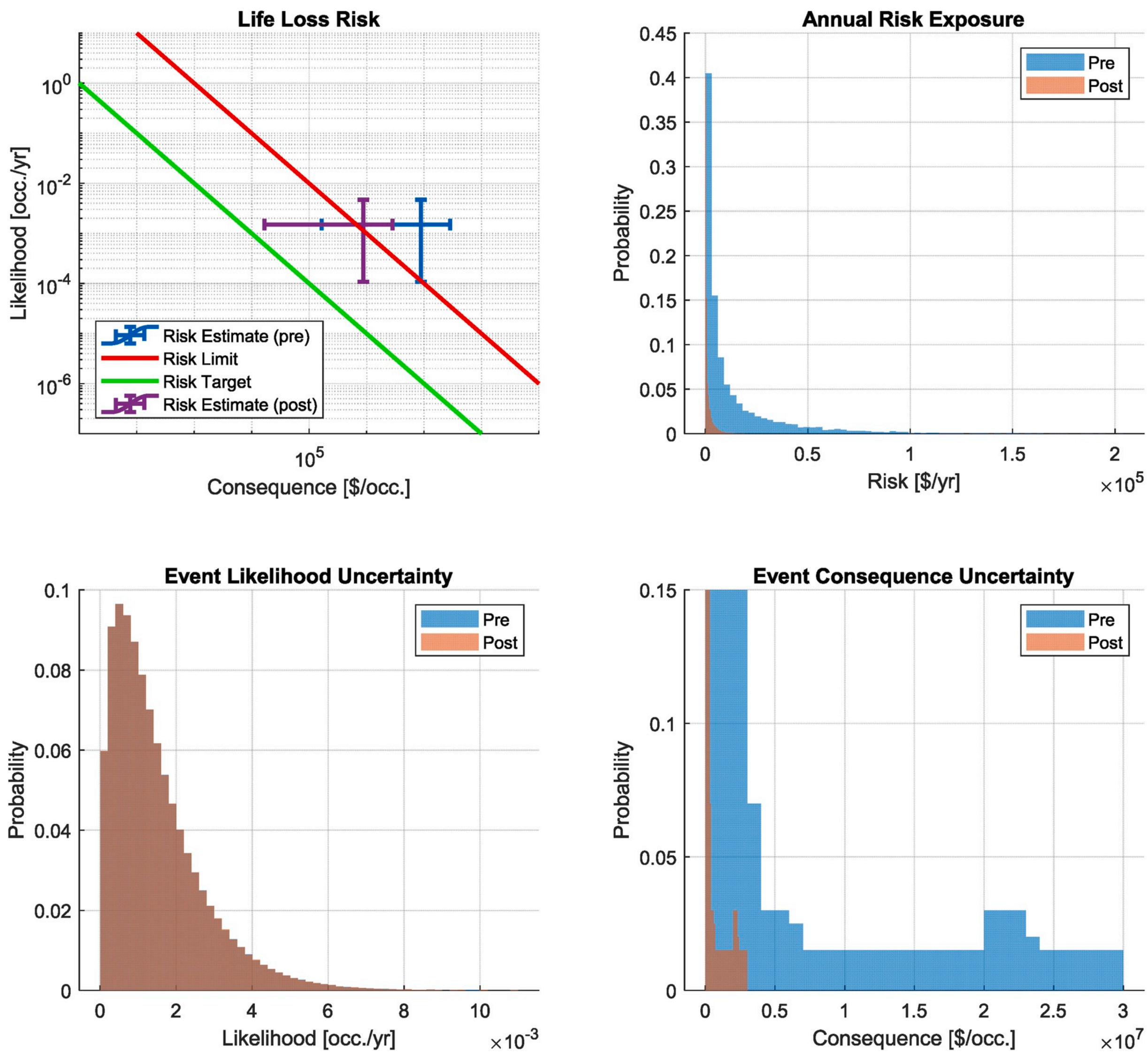


Fig. 17. Loss of life risk reduction – automation upgrades (treatment no. 1).

risk reduction afforded by option 2 under the assumption that option 1 has been implemented.

4.1.2. Prioritization

Prioritization of risk treatment options 1 through 4 (see Table 4) is done using the TOPSIS method and with weights derived using AHP as described in Section 3.2.3. The TOPSIS decision matrix is developed using the values for the first four alternatives in Table 5. The weights used for each criterion are summarized in Table 2. We do not review the details of the TOPSIS calculation in this paper. However, the TOPSIS decision matrix, normalized decision matrix, and treatment option closeness coefficients are provided in the Supplementary Material.

Final rankings of the treatment options are as follows:

1. Option 1 – Automation Upgrades
2. Option 3 – Fire Suppression System
3. Option 4 – Compressor Improvements
4. Option 2 – Pipework Replacements

The result of the prioritization exercise appears to be logically consistent. Automation upgrades provide the largest reduction in loss of life risk, as well as reducing the risk limit exceedance probability with respect to loss of life. Both measures are heavily weighted according to the decision-maker preferences assumed in this work. Options 3 and 4 improve production and property loss risk. Option 3 is ranked higher due to the lower cost, which is more heavily weighted than production and property loss risk reduction. Option 2 is ranked lowest, which is expected considering its high cost and relatively little risk reduction. That being said, since the project reduces the probability of exceeding the loss of life risk limit, the decision-maker could consider this project by virtue of the precautionary principle.

5. CONCLUSIONS

In this work we have presented a method for risk-informed decision making in the physical asset management context. The methodology uses quantitative risk measures for loss of life, loss of production and loss of property. A risk matrix is used to classify risk as intolerable, ALARP or broadly tolerable. Risks in the intolerable and ALARP region require risk treatment, and risk treatment options are generated. Risk reduction benefit of the treatment options is quantified, and cost-benefit analysis is performed using discounted cashflow analysis. Viable projects, as determined by positive NPV calculated in the cost-benefit analysis, are then prioritized using a combination of the AHP and TOPSIS MCDM/A methods. AHP is used to derive weights for prioritization criteria based on decision-maker preferences. The weights, along with prioritization criteria for risk reduction, tolerance criteria and project cost, are used to prioritize projects using the TOPSIS method.

Application of the proposed methodology will promote transparent risk-informed decision making in the physical asset management context. Decision-making is improved by the full transparency of the methodology by being open about the uncertainty in the risk measures. Rather than using expected values and a mechanistic decision process about risk tolerability, risk measures and associated uncertainty of the likelihood and consequence(s) are clearly demonstrated visually through a risk results dashboard. A decision-maker can take into consideration the probability of exceedance of the risk limits and targets. Furthermore, the utilization of AHP and TOPSIS provide a structured and transparent method to include decision-maker's preferences in the decision process. Using AHP, one can demonstrate how a decision-maker's selection of relative importance of risk treatment selection criteria translates into weights for each, which then affect how options are ranked. The usefulness of the methodology for improved decision making is illustrated using a numerical example.

CRediT authorship contribution statement

Zaki Syed: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. **Yuri Lawryshyn:** Conceptualization, Validation, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jlp.2020.104064.

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