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Abstract

The efficiency with which risks can be mitigated should be considered a critical factor in decisions regarding whether to mitigate or to create contingency funds instead of mitigating. Although an ensemble of risks is best treated with a numerical approach because of the inherent discreteness of mitigation, which occurs at specific times for specific risks, an analytic examination provides insight and a foundation for multiple-risk calculations. A formalism is created that suggests four zones of mitigation efficiency, from highly efficient to highly inefficient. If the efficiency turns inefficient before total mitigation is accomplished, the total expected cost of a risk reaches a minimum, beyond which it rises despite further mitigation. The total expected cost is created by adding the standard expected cost to the expended mitigation funds.

Key words: risk; mitigation; contingency; control; planning; decision analysis; project management

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1 Introduction

Both the popular press and much recent management literature have largely ignored the key comparison of the impact of a risk to the burden of its mitigation. A LexisNexis® *Academic* search of "Major World Publications" on 20 May 2008 found only 37 articles with either the word "mitigate" or "mitigation," but 1284 articles mentioning "risk," a ratio greater than 30. A search of author keywords in the EBSCO "Business Source Premier" Research Database on the same day revealed a similar focus on risk (6010 articles) as compared to mitigation (181 articles), again a ratio greater than 30; since the year 2000, only 10 *Risk Analysis* articles have considered "mitigation" a key word (and possibly only 3 earlier articles).

When looking at natural disasters, the insurance industry examines mitigation costs in comparison to expected losses, but with a broad-brush approach on scales large in time and geographical area.[1,2,3] Similarly, contingency in project management is often viewed at the project level rather than at the level of individual risks.[4,5] Yet intuitively we know that mitigation effectiveness should play a crucial role in deciding whether to mitigate specific risks or to accept them and set aside contingency funds. Here, we present a basic mathematical description of the competition between mitigation costs and the expected value of identified adverse impacts.

This analysis applies to any risks and their associated impacts, but we note specifically the perspective of managing projects. Although similar to the now-traditional "PRA" (Probabilistic Risk Assessment),[6] project management risk assessment differs from it in ways that have helped stimulate this research. Perhaps most important, projects progress by accomplishing tasks scheduled on a temporal network. The longest path through the network determines the project's duration, and a delay in any of the tasks on that network will delay the entire project. Delays in tasks not on this so-called critical path may, if sufficiently long in duration, also delay the project.[7] If they do not delay the project, they may delay future tasks. All delays cost money, but project risks materialize frequently and regularly. Although the collected effect from many delays (whether independent or not) can derail a project sufficiently to stop its progress before completion, usually only a tiny subset of the delays can cause total project collapse by themselves.

Because projects by definition create new structures or systems, project managers expect risks, and their mitigation strategies can include reducing risk probability and impact, but never does a project manager assume zero risk. After mitigation, project managers allow for contingency in the form of contingency funds.

In actual practice the mitigation of an individual risk occurs typically in one or more discrete steps, at one or several distinct times in the life of a project. Because of this inherent discreteness, useful treatment of an assemblage of risks requires a statistical, numerical approach, which we defer to a subsequent paper. Here we shall use a continuous approximation, but the parameter introduced can describe the behavior of either a discrete or continuous system with one or many risks.

For most of the remainder of this short paper, we ignore any temporal considerations and examine risks in terms of the mitigation of their impacts or probabilities. After this calculation, we touch on risks evolving in time, to consider briefly the possible effect of the loss of the contingency funds' accumulated interest.

We begin below by defining an efficiency term that quantifies the mitigation funds expended in terms of their efficacy in reducing a risk's expected value. Valid risk management decision-making depends on knowledge of that term and its dependence on other factors that can change as the system evolves.

2 A Risk Mitigation Analysis

2.1 The Expected Value of Losses

A proper mathematical definition of an expected (sometimes "expectation") value requires a distribution of the probabilities of the relevant variable. (New structures, i.e., the result of projects, often lack reference to the well-organized historical risk record generally needed for valid probabilities.) Despite the absence of a known distribution, 60 years ago the famous jurist Learned Hand first multiplied the probability of an "injury" by its cost to compare it to the "burden" of mitigation.[(8)] Since Hand's time, lawyers, economists, and managers have multiplied an individual risk's probability of occurrence (over the time of interest), P, by its impact, I, to determine its expected value, R:

$$R \equiv P \times I \rightarrow R_T = \sum_{i=1}^{n} P_i I_i,$$

where n is the total number of (identified) risks. The second expression shows the sum of individual expected values over multiple independent risks, which equals the total expected loss, i.e., the sum of the expected values of all the possible impact combinations; it characterizes the system of (independent) risks. We will frame the problem in terms of a continuous mitigation efficiency.

2.2 Mitigation Costs Are Sunk: A Measure of Mitigation Efficiency

Changes in expected value result from changes in either or both probability and impact:

$$dR_T = \sum_{i=1}^{n} I_i \, dP_i + \sum_{i=1}^{n} P_i \, dI_i.$$

Somewhat analogously to the "risk/cost functions" (which model probability reductions only) used in system reliability optimization problems,[9] we define the key parameter Θ as the ratio of the drop in the expected value of mitigated risks, dR, to the cost of mitigation (mitigation funds), dF_M:

$$\Theta(R) \equiv -\frac{dR}{dF_M}; \tag{1}$$

the minus sign keeps $\Theta > 0$ as R becomes smaller and the accumulated mitigation funding, F_M, grows larger.

For an individual risk, if we know how the mitigation efficiency depends on the risk's expected value, we can use Equation 1 to sum the costs as the risk's expected value decreases under mitigation:

$$F_M(R) = -\int_{R_0}^{R} \frac{dR'}{\Theta(R')}, \tag{2}$$

where R_0 is the risk's initial expected value.

2.3 Contingency Funds

Managers set aside contingency funds that they can use to deal with the impact after a potential risk has been transformed into an actual occurrence. Unlike the mitigation funds, F_M (Equation 2), which are spent and cannot be recovered, the contingency funds are simply set aside. If the risk does not occur, they can be returned.

Ideally, one would take a most conservative approach and define the impact as the cost to re-align a project with its pre-event plan.[10] In practice, one would need to anticipate the delays and disruptions that follow the initial event to determine this ultra-conservative number.[7,11] Many project teams therefore estimate — to their peril — the direct impact only. The validity of the estimated impact affects the implications of the following calculations.

For the sake of simplicity consider first a single risk with mitigation that affects impact only and not probability, so $dR = P dI$. The average mitigation efficiency, $\overline{\Theta}$, over a total reduction of risk, i.e., to $I = 0$, is given by PI/F_M.

If the I value truly estimates the long-term impact, allowing mitigation with $F_M > I$ makes no sense because complete mitigation then costs more than allowing the risk to occur and fixing the damage afterwards (and the event might not occur). We find the same result if we allow the impact to remain unchanged but mitigate the probability to zero. Thus, at any given time, for any given risk that we wish to consider for total mitigation, i.e., so that from P or I either the final probability or impact is zero, we have a lower limit on the subsequently required average mitigation efficiency:

$$\overline{\Theta} > P. \tag{3}$$

(The average efficiency under three models can be calculated from the expressions given in §4.2.)

More realistically, if management realizes that it does not understand well the so-called knock-on effects of the risk, mitigation, even with $\overline{\Theta} < P$, can make sense because of this (mis?)understanding that the actual risk will sometimes (often?) have an impact greater than the stated impact (leaving open the question of why management has not already adjusted the impact used in the expected value calculation). Also, from a psychological perspective, knowing that a risk has been mitigated fully reduces anxiety greatly; we do not consider here the difficult translation of the resulting equanimity into an equivalent cost.

Although organizations typically create a project contingency fund, F_C, by multiplying the total project budget by a (round-numbered!) fraction, e.g., 10 percent,[12] the fund clearly should instead be connected to the total R of the project, i.e., the total expected loss; we have $F_C \equiv F_C(R)$. In the case of a single risk in a single project we could write $F_C = (1/P) \times R$, whereupon $F_C = I$, as desired. Determining F_C for multiple risks demands a more sophisticated, statistical, algorithm,[10,13] and reducing the average probability of the n risks will lower F_C (although sometimes in a step-wise fashion).

Here we define the budgeted cost of contingency, C_B, and the total expected cost of the risks, C_E, to include any previously expended mitigation funds, F_M:

$$C_B = F_C(R) + F_M \tag{4}$$
$$C_E = R + F_M. \tag{5}$$

For an individual risk, where $F_C(R) = I$, we have $F_C(R) \gg R$, but even for an ensemble of risks, when one wants to allocate sufficient contingency funds to meet high statistical confidence levels of coverage, $F_C(R) > R$. Because F_C is a function of R, we expect that the general conclusions that we discover for the progression of C_E will hold for C_B, too. In general, however, we cannot determine $F_C(R)$ easily, and the calculations that follow will involve only C_E (Equation 5), which we term the *expected cost function*.

As mitigation is effected, the spent funds, F_M, grow but the expected value of the loss, R, decreases along with the current contingency fund, $F_C(R)$. The competition between the expected loss and F_M determines whether or not an optimum (minimum) cost exists. We begin by examining the case where Θ is independent of R.

3 Constant Mitigation Efficiency

In typical situations, mitigation efficiency will change as the expected value of a risk changes. However, we examine first this simplest case of constant Θ to understand better the interplay between the two terms that compose the expected cost function (Equation 5). For now, we let Θ equal the constant Θ_0. From Equation 2 we have:

$$F_M = \frac{1}{\Theta_0}\left[R_0 - R\right]. \tag{6}$$

We normalize the expected cost function to the initial expected value of the risks through $z \equiv R/R_0$ and $y \equiv C_E/R_0$. The evolution of the system will therefore show y as a function z; z begins at its maximum, 1, and declines to zero if the risk is mitigated fully. Thus, with constant mitigation efficiency we find the following normalized risk cost function:

$$y(z) = \left[1 - \frac{1}{\Theta_0}\right] z + \frac{1}{\Theta_0} \approx z + \frac{1}{\Theta_0}, \tag{7}$$

where the approximation on the right-hand-side holds during high mitigation efficiency, when $\Theta_0 \gg 1$; the normalized total expected cost at full mitigation (when $z = 0$) is always $1/\Theta_0$.

With or without this approximation, y evolves linearly with z. The first derivative shows the constant slope of the line,

$$\frac{dy}{dz} = 1 - \frac{1}{\Theta_0}, \tag{8}$$

and the second derivative is zero.

The slope will be positive when $\Theta_0 > 1$. In that case, z and y decrease as the system progresses. This constant reduction of the cost function implies *highly efficient* mitigation: the expected value of the risk (and perhaps also the contingency cost) falls more quickly than the mitigation expense rises.

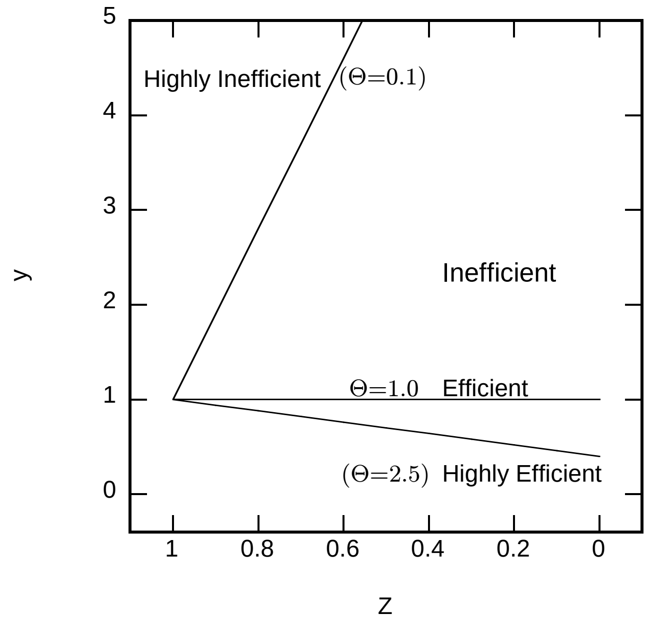

Fig. 1. An Example of the Four Efficiency Regimes at Constant Theta
As explained in the text, y is the normalized expected cost function, C_E/R_0, and z is the normalized expected cost of the impact, R/R_0. Note that $\Theta = 0.1$ as a border assumes a probability (or an equivalent probability) of 0.1; a different probability will shift the border. Similarly, any value of $\Theta \gtrsim 1$ could be used to illustrate the transition to the "highly efficient" regime.

At $\Theta_0 = 1$, the derivative is zero: *efficient* mitigation lowers a risk's expected value but leaves the total expected cost unchanged. If the risk vanishes ($R \to 0$), the total cost equals R_0/Θ_0, as seen from Equation 6. Kleindorfer and Kunreuther stipulated that the benefit gained from mitigation should exceed its cost (equivalent to requiring $\Theta_0 > 1$).[3] They did not address changing efficiency and they did not mention the cost-neutral ($\Theta_0 = 1$) possibility. Because of general anxiety about risks and great uncertainty about their estimated impacts, many organizations would be happy to proceed with this efficiency if in the end a risk no longer need be considered.

The negative slope of $\Theta_0 < 1$ shows *inefficient* but still effective mitigation as long as Θ for any individual risk remains greater than its minimum value, P, as shown above (Equation 3). Nevertheless, in this case the expected cost function, C_E, rises with declining R. Thus, when $\Theta < P$, we term the mitigation *highly inefficient*, but it can still reduce the risk to zero at $y_0 = 1/\Theta > 1$.

From this analysis of constant Θ, we summarize the four regimes of mitigation efficiency for any individual risk:

1) $\Theta > 1$: *Highly Efficient*
Expected cost function, C_E (Equ. 5), decreases monotonically.
2) $\Theta = 1$: *Efficient*
Expected cost function does not change (but risk is mitigated).
3) $P < \Theta < 1$: *Inefficient*
Expected cost function rises; cost of total mitigation $(R = 0) < I$.
4) $\Theta < P$: *Highly Inefficient*
Expected cost function rises; cost of total mitigation $> I$.

For collected risks, we can define an equivalent probability that is consistent with the above efficiency definitions. Because $R_T = \sum_{i=1}^{n} R_i$, we can sum the impacts to find $I_T = \sum_{i=1}^{n} I_i$ and define the equivalent probability as R_T/I_T. Figure 1 illustrates the four efficiency regimes.

4 Varying Mitigation Efficiency

4.1 General Analysis

If it were possible to maintain a large mitigation efficiency ($\Theta \gtrsim 1$) for all risks, most projects would see far fewer risks than they experience. Those risks that permit efficient or highly efficient mitigation are mitigated away, i.e., to $R = 0$. For most risks, however, all signs point to decreasing mitigation efficiency as mitigation continues. We show quickly now that unless the efficiency, Θ, can remain above 1, a minimum expected cost exists, beyond which increased mitigation spending raises the expected cost function.

We rewrite Equation 2 in terms of the normalized variable, z:

$$F_M(z) = -\int_1^z \frac{R_0\, dz'}{\Theta(z')},$$

and find

$$y = z - \int_1^z \frac{dz'}{\Theta(z')}.$$

The fundamental theorem of calculus yields the first derivative:

$$\frac{dy}{dz} = 1 - \frac{1}{\Theta(z)}. \tag{9}$$

If the second derivative,

$$\frac{d^2y}{dz^2} = \frac{1}{\Theta(z)^2}\frac{d\Theta}{dz}, \tag{10}$$

is greater than zero, a minimum in the expected cost function (Equation 5) can exist, and Equation 10 thus yields the first, unsurprising, condition necessary for this minimum: $d\Theta/dz > 0$. If the efficiency, Θ, falls as mitigation lowers the risk's expected cost, R, the expected cost function will reach a minimum when the first derivative (Equation 9) equals zero, which occurs at $\Theta(z) = 1$. These conditions assure us that while the efficiency remains above 1, all the costs used to lower a risk's probability or impact also lower the total expected cost, C_E (Equation 5). If the efficiency should drop below one, additional mitigation lowers the expected value of the risk but raises the total expected cost. We next look quickly at several functional examples.

4.2 Three Example Efficiency Approximations

4.2.1 Linear

If $\Theta = \Theta_0 + mz$, Θ_0 is the efficiency at $z = 0$, and at $z = 1$ the original efficiency is given by $\Theta_1 = \Theta_0 + m$. If $m > 0$, the first derivative is positive, and a minimum exists at:

$$z_m = \frac{1 - \Theta_0}{m}.$$

Because $z > 0$, the minimum can only exist if $\Theta_0 < 1$ (otherwise mitigation has removed the risk before this point is reached), and because $z \leq 1$, $\Theta_0 + m = \Theta_1 \geq 1$, as expected.

4.2.2 Power Law

If the ability to mitigate risks shows a Pareto-like dependence, mitigation efficiency might behave as a power law: $\Theta(z) = \Theta_0 + \Theta_1 z^\alpha$, where $\alpha > 1$, $\Theta_1 + \Theta_0$ is the original efficiency, and Θ_0 is the efficiency when the risk has been mitigated totally (to $z = 0$). Again a positive derivative $d\Theta/dz$ allows a minimum, at:

$$z_m = \left(\frac{1 - \Theta_0}{\Theta_1}\right)^{1/\alpha},$$

which imposes the expected conditions for a minimum: $\Theta_0 < 1$ and $\Theta_1 + \Theta_0 > 1$.

4.2.3 Exponential

In a manner analogous to the way in which the utility of risk aversion is modeled with an exponential function (whence increasing expenses yield proportionately smaller utility) or the reliability risk-cost function is also often modeled exponentially,(9) for many risks mitigation efficiency may shrink exponentially:

$$\Theta = \Theta_0 \exp(\kappa z), \tag{11}$$

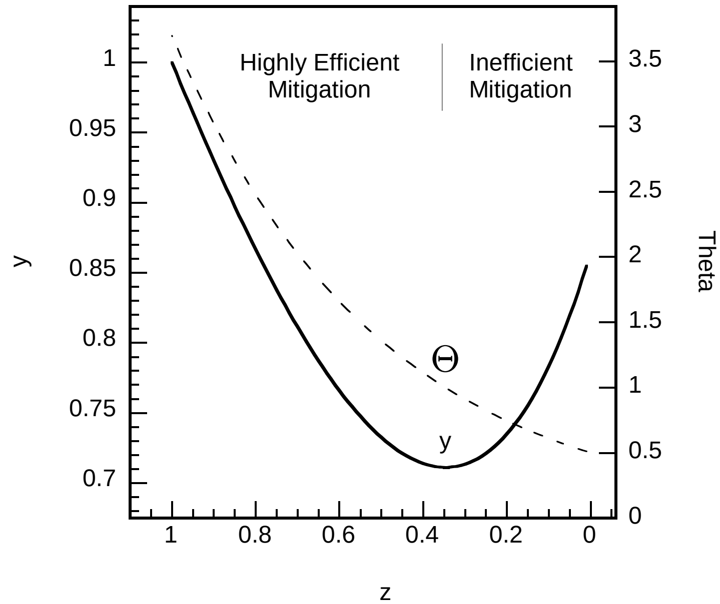

Fig. 2. Exponentially Evolving Mitigation Efficiency
An exponential decay in the mitigation efficiency leads to an increase in the expected cost once the efficiency drops below 1; $\Theta_0 = 0.5$, $\kappa = 2$, with a resulting minimum in y at $z_m = 0.347$ (Equation 13).

where the dimensionless constant $\kappa > 0$ controls the strength of the change in Θ. (With this formalism, we could also allow $\kappa < 0$ to simulate an increasing mitigation efficiency, which may occasionally be possible; we do not examine that case here.) The constant, Θ_0, is again the mitigation efficiency in the limit that $R \to 0$, and the original efficiency is $\Theta_1 = \Theta_0 \exp(\kappa)$.

In this example, we also show the normalized function, y. Because of the Θ dependence in the expected cost function (Equation 5), $F_M = \{\exp(-\kappa)/\kappa\Theta_0)\}\{\exp(\kappa[1-z]) - 1\}$, and we find:

$$y = z + \frac{1}{\kappa\Theta_1}\left\{\exp(\kappa[1-z]) - 1\right\}.$$

In the limit that $\kappa \to 0$, this expression reduces to the $\Theta = \Theta_0$ case seen in Equation 7. At $z = 0$ (complete mitigation), we have

$$y(0) = \frac{\exp[\kappa] - 1}{\kappa\Theta_1}. \tag{12}$$

A minimum can occur at

$$z_m = -\frac{\ln(\Theta_0)}{\kappa}, \tag{13}$$

which, when used in Equation 12, delivers

$$y(z_m) = \frac{1}{\kappa}\left\{1 - \ln(\Theta_0) - \frac{1}{\Theta_1}\right\}. \tag{14}$$

When $\kappa > 0$, this condition can again occur only when $\Theta_0 < 1$ and $\Theta_1 > 1$.

Figure 2 shows an example of $\Theta_0 = 0.5$ and $\kappa = 2$. The minimum in the expected cost function occurs at $z_m \simeq 0.35$ (Equation 13), and $y(z_m) \approx 0.71$ (Equation 14). These numbers mean that the risk's expected value has been reduced by 65%, which would generally be considered excellent mitigation. However, the true comparison, to the total expected cost (Equation 5), shows a decease to 71% of the original, a drop of only 29%. If mitigation continues, the total expected value begins to rise, finally peaking at about 86% (Equation 12) when the risk has been mitigated away — a potential savings of only 14%.

5 Additions in Time and Number

5.1 Time Adds a Component to The Expected Cost Function

Whether or not the risk transpires, the organization loses flexibility in the contingency funds for the duration of the risk. The organization loses interest on the money because the contingency funds should remain relatively fluid (to be available for quick use should the need arise), and if they earn any interest, the best rates will most likely not be attainable. To calculate the loss we must introduce time into the formalism.

We can write this opportunity cost in terms of the lost-interest rate, i, that multiplies the contingency fund. We assume a constant i, but to account for the decrease of the contingency fund (as risks are mitigated), we integrate the fund through time to determine the total interest revenue lost:

$$F_i(t) \equiv i \int_0^t F_C(t')\, dt'. \tag{15}$$

These funds should be added to the expected cost function, C_E (Equation 5), but not to the budgeted cost, C_B (Equation 4):

$$\begin{aligned} C_B &\to F_C(R) + F_M \\ C_E &\to R + F_M + F_i. \end{aligned}$$

Although $F_C \gtrsim R$, this additional term in the expected cost function at least opens the possibility that it can grow larger than the budgeted cost, i.e., $C_E > C_B$.

As discussed earlier, for an individual risk, $F_C = I$, but knowing the evolution of R through Θ does not provide the necessary information about the separate components P and I that would be needed for the integration using I. Thus, because we do not know the general dependence of F_C on the expected value, Equation 15 yields little additional information now. We merely point out its existence and note that its importance will grow with low mitigation efficiency, where it could raise the y value of the minimum point and increase the z value at which it occurs.

5.2 Extension to Multiple Risks: The Expected Value of Losses

Extending an analytic calculation such as this to multiple risks presents two main difficulties. First, a proper determination of expected values for n multiple risks may require calculating the 2^n combinations of different risks occurring. The combined probabilities (for some risks occurring and others not occurring) must be multiplied by the combined impacts of the occurring risks. Second, in most long-term efforts, mitigation of risks would occur at different times, with a new calculation of the total expected cost occurring after each change. These two constraints necessitate a numerical simulation, which we are in the process of executing.

6 Summary and Expected Benefits

We have introduced a simple formalism to examine the total expected cost of risks in the presence of a mitigation cost component: the direct expected cost of a risk's impact is added to the funds used for mitigation. The formalism removes the binary approach often seen in mitigation analyses, where risks are considered either mitigated or not mitigated. By including the cost of the mitigation, the formalism encourages continuous estimations of a risk's expected value as it changes because of mitigation.

The combination of spent and probabilistic funds highlights four regimes of mitigation efficiency, from highly efficient, where the new expected cost function decreases monotonically, to highly inefficient, where the function rises and the total cost required to mitigate a risk fully (so that $R = 0$) grows to become larger than the estimated cost of a risk's impact, I.

Inefficient mitigation, when Θ becomes less than one, can lead to a minimum in the expected cost function. While managers should attempt to reach this minimum, additional mitigation does not benefit an organization that has estimated well its risks and their impacts.

This work thus shows the benefits of good risk estimates, not only in terms of probability and impact, but also in terms of the varying efficacy of mitigation. An awareness and an understanding of real mitigation efficiencies can guide risk mitigation priorities; organizations can direct resources to those risks where they will find the best return on their mitigation investment. Thus, organizations have further incentive for improving their estimates of risk probabilities and impacts. If an organization truly believes a risk impact estimate, and if it understands the effectiveness of its mitigation, it now has the tools to make an objective decision about when to stop mitigating a risk and instead set aside contingency funds.

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