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Challenges in the Evaluation of Ultra-Long-Lived Projects: Risk Premia for Projects with Eternal Returns or Costs

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Abstract

The economic evaluation of ultra-long-lived investment projects is not only challenging due to the choice of the planning horizon but also due to the discounting of future uncertain cash flows. Thus, for real world investment decisions a better understanding of the project's risks and their effect on the project's value is crucial. If long-term investments are modeled, stochastic processes may be used to reflect the uncertain development of future prices and cash flows. The choice of the stochastic process is consequently an essential assumption in the modeling process. This paper critically discusses the risk of ultra-long-lived investment projects implied if future pay-off's are assumed to follow geometric Brownian motion processes. In our analysis, we distinguish between projects driven by costs and such driven by revenues. For both kind of projects we compare the value at risk with the returns of a risk-free asset. Therein, the value at risk describes the threshold value of the confidence levels of the uncertain cash flow's probability density function. The comparison for long time horizons shows that the lower confidence interval exceeds the returns of a risk-free asset used as a benchmark for any choice of the confidence level, which implies that the returns of a "worst-case" scenario (within the assumed confidence interval) will still exceed the returns of a risk-free asset in the long-term perspective. For the case of uncertain future cost, the risk measure is defined as the difference between the expected value and the boundary of the confidence interval. This value is also found to become negative in the long-term perspective.

Key words: Ultra-long-lived projects, discounting, risk evaluation

1 Introduction

Ultra-long-lived projects are characterized by lifetimes which in general exceed the planning horizon of the investor (Energy, Mobility & Environment Research Group, EME, 2013). Thus, long-term future consequences either for the investor himself or for any other stakeholder are usually neglected in the decision process. Such ultra-long projects are typically infrastructure investments with very long life cycles, as they are often found in the energy sector (power plants, grids, nuclear waste deposits, etc.). A general classification of ultra-long lived projects can be the distinction between long-term revenue- and long-term cost-driven projects. The former are related to expected future revenues (and costs), whereas the latter only imply costs. Examples for the first category are, for instance, investments in fundamental research, or site and infrastructure development, while examples for projects with eternal cost are nuclear waste deposit or carbon dioxide storage sites.

Mathematically speaking, the problem of ultra-long lived projects becomes obvious in the calculation of an investment's net present value (NPV),

$$\mathrm{NPV} = \int\limits_{0}^{T_{\mathrm{P}}} CF(t)e^{-\delta t}dt - I \neq \int\limits_{0}^{\mathrm{E}} CF(t)e^{-\delta t}dt - I. \tag{1}$$

where $CF(t)$ denotes the cash flow in time t, δ the discount rate which weights future cash flows according to their appearance, and I the investment costs. The problem of incorrect decisions arises if the planning horizon T_{P} is smaller than the effective time horizon T_{E} and if the cash flows between T_{P} and T_{E} have a significant influence on the investment's value and, consequently, on the investor's decision (and his and other stakeholders' well-being) (Energy, Mobility & Environment Research Group, EME, 2013).

A similar discrepancy in the decision-making process can result from an incorrect weighting of future cash flows, e.g. due to an inadequate discount rate δ.

$$\mathrm{NPV} = \int\limits_{0}^{\infty} CF(t)e^{-\delta_{\mathrm{assumed}} t}dt - I \neq \int\limits_{0}^{\infty} CF(t)e^{-\delta_{\mathrm{correct}} t}dt - I \tag{2}$$

Although the cause of defect appears to be different in equations (1) and (2), an overestimated discount rate often misleads decision-makers to neglect effects and cash flows of future periods due to their low weighting in the decision process and thus to a truncated planning horizon.

In the paragraph above, we have introduced the discount rate δ, which in general reduces the value of future cash flows. We have also mentioned that those discount rates can be chosen “incorrectly”. To discuss the problem of “correct” and “incorrect” discount rates the general idea and purpose of discounting should be recalled. First, discounting can be seen as a way to evaluate future cash flows, taking into account the availability of alternative investment options. This implies that returns gained today can be reinvested and thus have a higher value compared to returns gained in future periods. This idea of discounting does not imply any kind of risk or uncertainty in future cash flows. If future cash flows are uncertain and the investor is risk-averse, the value of those future cash flows reduces further. This can be modeled by using higher (risk-adjusted) discount rates, such as prescribed by the classical capital asset pricing model (CAPM; Sharpe, 1964; Lintner, 1965). However, higher discount rates imply a constant increase of the future cash flows’ uncertainty. Such a constant increase in uncertainty might be avoided if the decision -maker can counteract risk in the course of the investment’s lifetime, e.g. by applying continuous hedging strategies.

In order to assess risk or risk patterns of ultra-long lived investment projects the returns of future cash flows have to be analyzed. For predicting those future cash flows by economic models it is necessary to properly understand the uncertainty, inherent in real world investment decisions, and to properly understand the risk, which is predicted by the choice of the model. Although the first part of this problem appears to be the most challenging and case-specific, the second part is no less complicated when addressing long-term predictions.

This paper investigates in-depth the long-term risk which results from choosing a geometric Brownian motion process for the modeling of future cash flows. Such processes are often assumed in real options analysis, which have also been used for the prediction of long-term investments (Rohlfs and Madlener, 2013).

The remainder of this paper is structured as follows. Section 2 introduces the geometric Brownian motion process as well as its basic characteristics. Section 3 deals with the evaluation of positive pay-offs at the end of the project’s lifetime and with the evaluation of positive cash flows during the entire project’s lifetime. In section 4, the uncertainty of negative cash flows is investigated, while section 5 concludes.

2 Risk structures of the geometric Brownian motion

The geometric Brownian motion (GMB), named after the botanist Robert Brown, is a stochastic process commonly used in mathematical finance to model price developments, especially in real options theory (Dixit and Pindyck, 1994; Hull, 2008), as for instance in the model of Black and Scholes (1973). In this continuous-time process the logarithm of the price follows a Brownian motion, e.g. a Wiener process (Wiener, 1923). The stochastic differential equation of the GBM reads

$$\frac{dS(t)}{S(t)} = \mu dt + \sigma dZ, \tag{3}$$

where μ is the growth rate or drift, σ is the volatility and dZ is the increment of a Gauss-Wiener process. The probability density function (PDF) of the price S_t with constant volatility and drift at a given point in time, t, is log-normally distributed and reads as

$$\mathrm{PDF}(s;\mu,\sigma,t) = \frac{1}{\sqrt{2\pi}}\frac{1}{s\sigma\sqrt{t}}\exp\left(-\frac{\left(\ln s - \ln S_0 - \left(\mu - \frac{1}{2}\sigma^2\right)t\right)^2}{2\sigma^2 t}\right), \tag{4}$$

where S_0 denotes the initial value at $t = 0$ and s is the price (Øksendal, B., 2003). The average value of this PDF, e.g. the expected value, is

$$E(S) = S_0 e^{\mu t} \tag{5}$$

and the variance

$$Var(S) = S_0^2 e^{2\mu t}\left(e^{\sigma^2 t} - 1\right). \tag{6}$$

The analytical expression for the variance shows a monotonic increase in time, suggesting a continuously rising level in uncertainty and, consequently, a growing level of risk.

Integration of the PDF (4) yields the cumulative distribution function (CDF) (Weisstein, 2013)

$$\mathrm{CDF}(s;\mu,\sigma,t) = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\left(\ln s - \ln S_0 - \left(\mu - \frac{1}{2}\sigma^2\right)t\right)}{\sigma\sqrt{2}\sqrt{t}}\right), \tag{7}$$

whereby erf denotes the Gaussian error function.

The mode, e.g. the position of the probability density function's global maximum

($\partial \mathrm{CDF}(s;\mu,\sigma,t)/\partial s = 0$), can be specified as

$$\mathrm{mode}_{S_t}(s;\mu,\sigma,t) = S_0 \exp\left((\mu - \frac{3}{2}\sigma^2)t \right). \tag{8}$$

Figure 1 illustrates the temporal development of the geometric Brownian motion process for the parameter set $\mu = 0.10$, $\sigma = 0.15$, and $S_0 = 1$. The three blue-colored paths are random examples of the stochastic process. The three blue-shaded areas illustrate the shape of the PDFs for $t = 5$, $t = 15$ and $t = 25$ years. The upper dashed blue line and the lower dashed red line depict the edge of the 25 percent quantile, such that the yellow highlighted region covers the inner 50 percent interval of the PDF. Due to the logarithmic distribution, the mean value (solid red line) of the process is not located in the center of the illustrated interval. Furthermore, the maximum of the PDF (i.e. the mode) surpasses the interval in the course of time (here at $t \approx 21$ years).

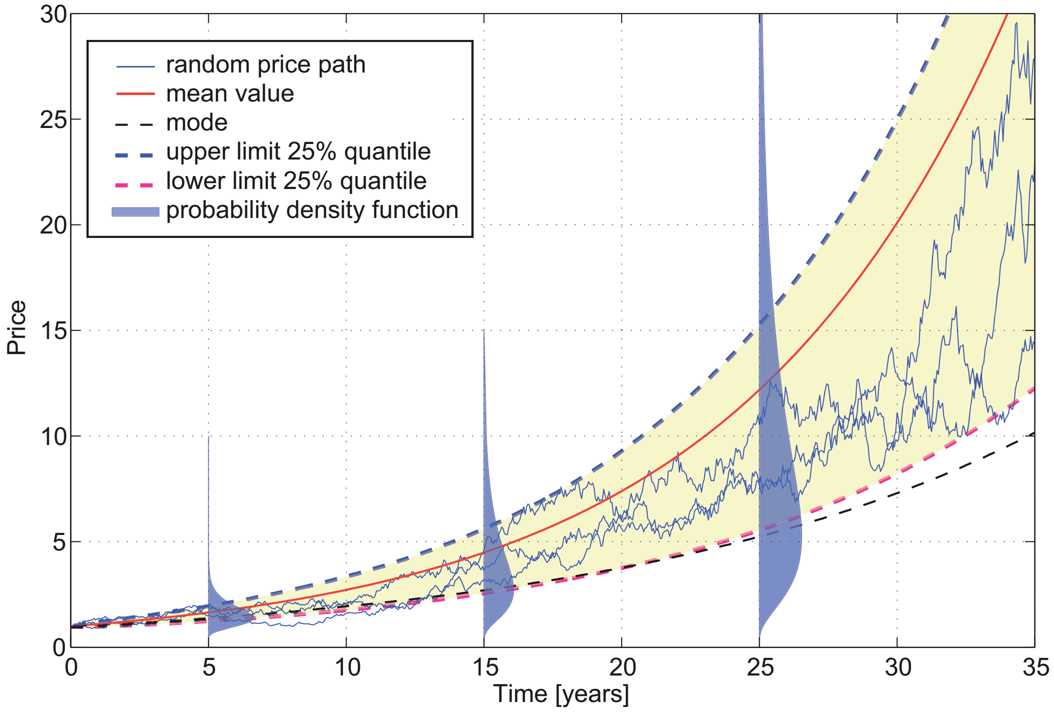


Figure 1: Illustration of a geometric Brownian motion process for $\mu = 0.10$, $\sigma = 0.15$ and $S_0 = 1$.

For the evaluation of ultra-long-lived projects a special focus is put on the long-term risk characteristics of the GBM process, dealt with in the following.

3 Evaluating investments with uncertain returns

For investigating the long-term risk characteristics of a GBM process a measure of risk needs to be defined. In the previous section, the most simplistic risk measure, the variance (6), has been introduced, showing a continuously increasing risk of the cash flows associated with the price development. Another widely used measure for the risk of loss in financial mathematics and financial risk measurement is the value at risk (VaR) (Sadeghi and Shavvalpour, 2006). This value defines a threshold or confidence level of the PDF such that with a confidence level α $(0 < \alpha < 1)$ losses do not exceed a certain value. In other words, the VaR describes the loss that can occur at a given confidence level (with the confidence level α), due to exposure to market risk (Holton, 2013). In practice, the confidence levels $\alpha = 1\%$ and $\alpha = 5\%$ are commonly used.

To calculate the VaR for the case that the value of an investment follows a GBM process, a reference state needs to be defined. The deviation from the reference state in the negative direction characterizes losses. Although the value of S_0 could be used as a reference, for long-term investments it is more appropriate to define losses as the difference between the performance of a risk-free asset (with the risk-free rate r_f) and the performance of the GBM process. Thus, the VaR is the threshold of the confidence level α of the performance of a risky asset compared to a risk-free asset. Mathematically, this value follows from the CDF as

$$\mathrm{VaR}_\alpha(\mu, \sigma, t) = S_0 e^{r_f t} - s\left(\mathrm{CDF}(\mu, \sigma, t) = \alpha\right). \tag{9}$$

Note that with this definition a positive VaR indicates losses. For the GBM process, the VaR can be analytically calculated by rearranging equation (7), and solving for the value of s

$$\mathrm{VaR}_\alpha(\mu, \sigma, t) = \underbrace{S_0 e^{r_f t}}_{\mathrm{RFA}} - \underbrace{S_0 \exp\left(\mathrm{erf}^{-1}\left[2\alpha - 1\right] \cdot \sigma\sqrt{2t} + \mu t - \frac{1}{2}\sigma^2 t\right)}_{\mathrm{CDF}_\alpha} \tag{10}$$

The equation above indicates that the VaR increases if the exponent of the CDF threshold (CDF_α) is lower than the exponent of the risk-free asset (RFA). Note that the value of the inverse of the error function is below zero for small values of α, e.g. $\alpha < 0.5$.

3.1 Investments characterized by a single pay-off

Figure 2 graphically compares the temporal development of the RFA and CDF_α. The four blue-coloured lines represent the ratio between the two values for different confidence levels α. The markers indicate a time interval of 5 years, whereas the red solid line with an angle of 45 degrees separates the region in which the value of the risk-free asset is higher than the threshold of the stochastic process, and vice versa. For all four values of α, the threshold value of the CDF_α decreases initially from the start value $[S_0, S_0]$ at $t = 0$. However, after a certain duration of time the CDF_α value starts to increase in time, eventually surpassing the red line. The inception point is equivalent to the statement that the VaR is zero according to eq. (10). From a mathematical perspective, the time of inception can be calculated by

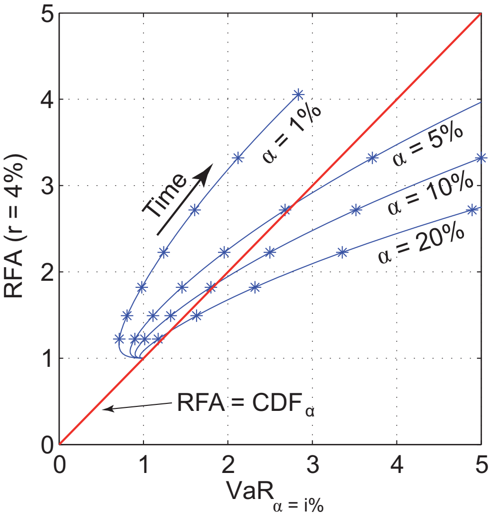
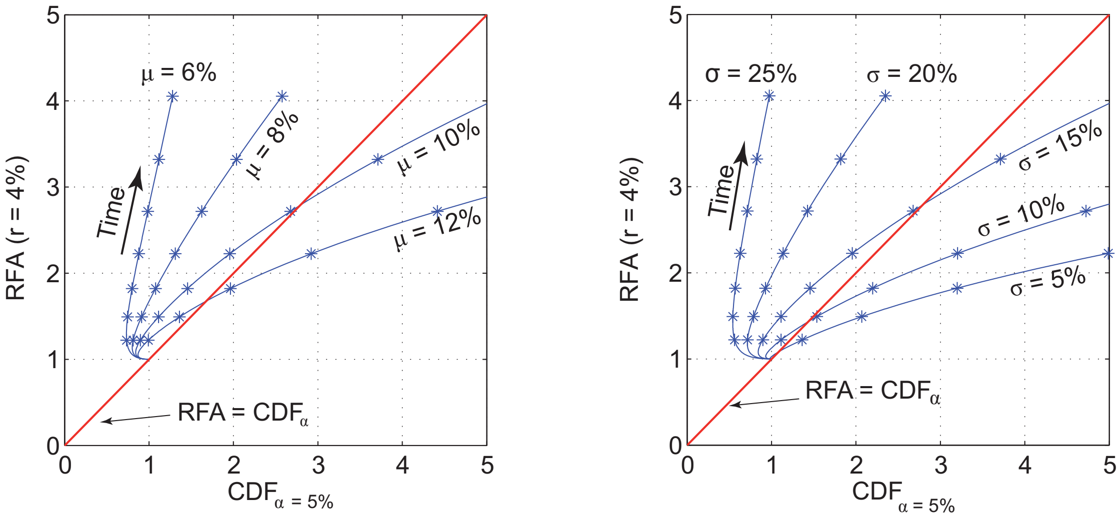


Figure 2: Comparison between the temporal development of a risk-free asset with the growth rate $r_f = 0.04$ and the confidence level α of a GBM process with the parameters $\mu = 0.10$ and $\sigma = 0.15$. The distance between two markers symbolizes a time span of 5 years.

$$t(\mathrm{RFA} = \mathrm{CDF}_\alpha) = \left(\frac{-\mathrm{erf}^{-1}(2\alpha - 1)\sqrt{2}\sigma}{\mu - r_f - \frac{1}{2}\sigma^2} \right)^2, \tag{11}$$

where erf^{-1} denotes the inverse error function. The equation shows that for $\mu > r_f + 1/2\sigma^2$ the confidence level (CDF_α) exceeds the returns of a risk-free asset independently from the choice of α. Thus, for ultra-long-lived projects it follows that the VaR becomes negative if the geometric Brownian motion process is chosen to characterize the value of future pay-off's. Consequently, the returns in a worst-case scenario will exceed the returns of a risk-free



(a) Variation of growth rate μ ($\sigma = 0.15$) (b) Variation of volatility σ ($\mu = 0.10$)

Figure 3: Parameter variation in the comparison between the temporal development of a risk-free asset with the growth rate $r_f = 0.04$ and the confidence level $\alpha = 5\%$ of a GBM process. The distance between two markers symbolizes a time span of 5 years.

asset in the long-term perspective.

Figure 3(a) depicts the influence of the growth rate μ on the intersection point of the confidence level $\text{CDF}_{\alpha=5\%}$ with the growth of the risk-free asset (with $r_f = 0.04$). The plot shows a shift of the intersection point to lower times if the growth rate of the asset increases, and vice versa. For a growth rate of $\mu = 6\%$, the graph still diverges from the 45 degree line at $t = 35$ years. The time of intersection according to equation (11) is as late as $t(\text{RFA} = \text{CDF}_\alpha) = 795$ years. A similar bandwidth of solutions is found for a variation of the parameter σ (with a constant growth rate of $\mu = 10\%$), shown in plot 3(b). Here, the time of intersection increases with the volatility.

3.2 Investments characterized by continuous cash flows

In the previous subsection investments have been analyzed which yield a single pay-off at the end of the time horizon. However, long-term investments, such as for instance new power generation units, are often characterized by continuous cash flows during their entire lifetime. Thus, it is necessary to sum up the cash flows gained in different periods and to analyze the risk of the combination of cash flows. This summation proves to be problematic from the analytical point of view if the cash flows follow an underlying stochastic process such as the GBM, because of the correlation between the GBM's distribution in different times. Note that this correlation does not violate the characteristic of the Markov-Process for which the subsequent state depends on the current state and not on the preceding events. The correlation between the different time steps can be explained by comparing the subsequent prices following a low-price and a high-price scenario. In the case of the low-price scenario, the subsequent value will either rise or fall, while the probability to rise or fall is independent from the history of the process. The same up- and downward movements will occur in the case of the high-price scenario. However, the high price following the low-price scenario will (most probably) be lower compared to the lower price following the high-price scenario. Thus, for risk analysis it is necessary to take this correlation adequately into account.

A second obstacle in the summation of cash flows gained in different periods is the reduced value of future cash flows, for which discounting is commonly applied. However, the application of a discount rate for uncertain cash flows includes already a risk premium in models like the CAPM. If the risk structure of the uncertain cash flows is meant to be retained, only a time-discounting is required, for which we choose here to discount the uncertain cash flow with the risk-free discount rate r_f. Hence, PDF* denotes the probability function of the risk-free discounted and summarized cash flows resulting from a continuous stream of positive returns.

The loss of simple analytical tractability of the problem requires the use of the Monte Carlo simulation technique in order to calculate both the probability density function PDF* and the confidence levels of the cumulative distribution function (CDF$^*_\alpha$) numerically.

Figure 4 shows the temporal development of the risk-free asset (RFA*) and the confidence level α of a risky asset (CDF$^*_\alpha$), both discounted by the risk-free rate r_f. It is assumed that the value of the yearly cash flows is initially one, e.g. $S_0 = 1$. Contrary to the previous graphs (Figs. 2-3), which started at the point $[1, 1]$, these plots originate at $[0, 0]$ because the integration of the yearly cash flows between time $t = 0$ and $t \to 0$ yields a zero return. The returns of the risk-free cash flows, discounted with the risk-free rate r_f, increase linearly in time (shown by the equidistant spacing between the marker symbols in the vertical direction). The confidence levels $\alpha = [5\%; 10\%; 20\%]$ of the risky cash flows surpass the cash flows gained from the risk-free asset in the depicted time interval. Only for $\alpha = 1\%$

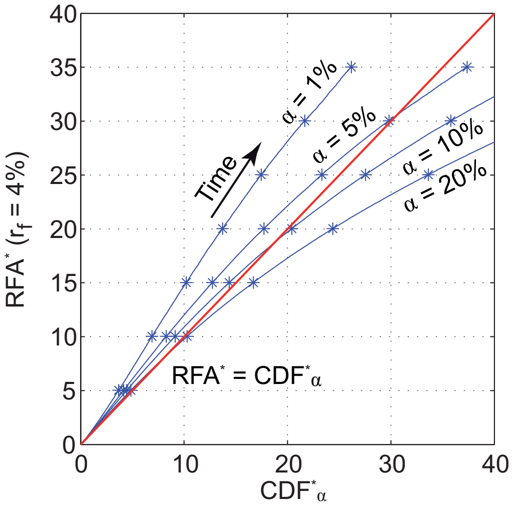


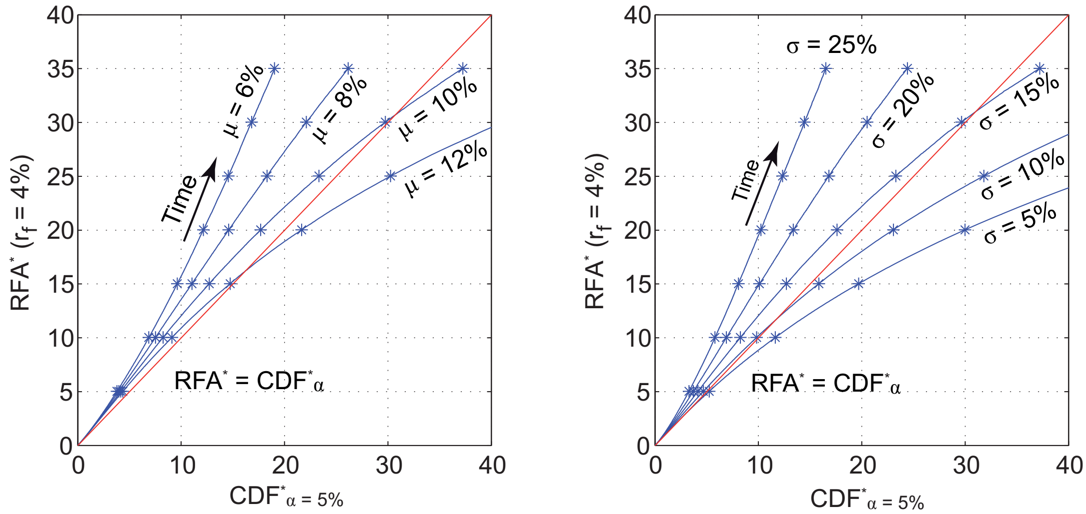
Figure 4: Comparison between the temporal development of risk-free continous cash flows with the growth rate $r_f = 0.04$ and the confidence level α of cash flows defined by a GBM process with the parameters $\mu = 0.10$ and $\sigma = 0.15$, both discounted by the risk-free rate r_f. The distance between two markers symbolizes a time span of 5 years.

the time needed to surpass this value is longer than 35 years. In comparison to the results found for the case of non-continuous cash flows (Fig. 2), the intersection point is delayed to later times in order to compensate for losses from earlier periods.

Figure 5 depicts the influence of the growth rate μ and the volatility σ. With increasing volatility and decreasing growth rate, the time needed until the cash flows from the lower confidence interval equal the returns of the risk-free cash flows increases. These results are in line with the ones of the single pay-off cases shown in the previous subsection.

4 Evaluating investments with uncertain eternal cost

The previous section dealt with the problem in which an investor pays initial investment costs (I) and receives returns at the end or during a defined period of time. For those investments, a risk premium is demanded by the investor if uncertainties are present. The risk premium reduces the present value of the future cash flows to a higher extent than a risk-free discounting does. In this section, the opposite problem will be analyzed in which an investor, e.g. an insurance company, receives an initial pay-off in order to guarantee for the payment of future cost, i.e. negative cash flows. Mathematically, this problem can be



(a) Variation of the growth rate μ ($\sigma = 0.15$) (b) Variation of the volatility σ ($\mu = 0.10$)

Figure 5: Parameter variation in the comparison between the temporal development of a risk-free asset with the growth rate $r_f = 0.04$ and the confidence level $\alpha = 5\%$ of continuous cash flows defined by a GBM process. The time span between two markers is 5 years.

written as

$$\text{NPV} = P + \int_0^{T_P} CF(t) e^{-\delta t} dt \text{ with } CF(t) < 0, \tag{12}$$

where P denotes the initial pay-off and $CF(t)$ denotes the negative future cash flows. Practically, such problems in the context of ultra-long-lived projects are of high interest, for instance, in the case of nuclear waste management or for determining the eternal costs of carbon storage sites (Toth and Miketa, 2011).

If the CAPM is applied to this problem in its standard form, the risk-adjusted discount rate δ is higher than the risk-free discount rate, which leads to the curiosity that the investor, for a given return, is willing to pay money for the acceptance of risk. To avoid this inconsistency, a discount rate for negative cash flows can for instance be derived on the basis of the risk premium. Here, we assume that the risk premium for positive returns is the difference between the present value discounted with the risk-adjusted rate and the present value, discounted with the risk-free rate, i.e.

$$RP^{+}(t) = CF^{+}(t) \left(e^{-r_f t} - e^{-\delta^{+} t} \right). \tag{13}$$

Postulating that the risk premium for positive returns equals the risk premium for negative returns ($RP^+(t) = RP^-(t)$), if the uncertainty of the cash flow is equal ($CF^-(t) = -CF^+(t)$), yields

$$RP^-(t) = CF^-(t)\left(e^{-r_f t} - e^{-\delta^- t}\right). \tag{14}$$

This leads to the condition

$$2e^{-r_f t} = e^{-\delta^- t} + e^{-\delta^+ t}, \tag{15}$$

and thus to the solution for the variable δ^-:

$$\delta^- = -\frac{\log\left(2e^{-rt} - e^{-\delta^+ t}\right)}{t}. \tag{16}$$

According to the equation above, a time-constant discount rate for positive cash flows results in a time-dependent discount rate for negative cash flows in order to maintain an equal risk premium. Furthermore, the discount rate δ^- can take negative values, as the following example with a given cash flow of 100 units at time $t = 5$, a risk-free discount rate of $r_f = 0.04$, and a risk-adjusted discount rate of $\delta^+ = 0.10$ illustrates. The present value of the cash flow discounted with the risk-free rate is 81.87, and 60.65 when discounted with the risk-adjusted rate. Thus, the investor receives a risk premium of 21.22 in today's money. If the cash flow is negative and the investor requires the same risk premium, the risk-adjusted present value has to take a value of 103.09 ($= 81.87 + 21.22$). This present value is higher than the cash flow of 100 (valued at $t = 5$). For risk-adjusted discounting, a negative discount rate of $\delta^- = -0.0026$ follows, which is in line with the solution of eq. (16).

The above-described method for discounting negative cash flows as well as the numerical example illustrate the complexity of evaluating eternal costs afflicted with uncertainty.

4.1 Long-term risk characteristics of eternal costs

In analogy to the discussion of long-term risk structures evolving from the basic assumption that revenues follow a geometric Brownian motion process, the present section investigates the risk structure for costs following this particular stochastic process. If the cost development is not prone to uncertainty ($\sigma = 0$), an investor can calculate the money needed to be deposited at a risk-free rate r_f in order to pay for all future costs. In the case of uncertainty in the magnitude of the future expenses, a risk premium will be requested because of the probability that the actual costs exceed the expected ones. In the following, we investigate the VaR under the assumption that the PDF of the future costs can be described by the course of a GBM process for the parameters $\mu = 0.10$, $\sigma = 0.15$, and $S_0 = 1$.

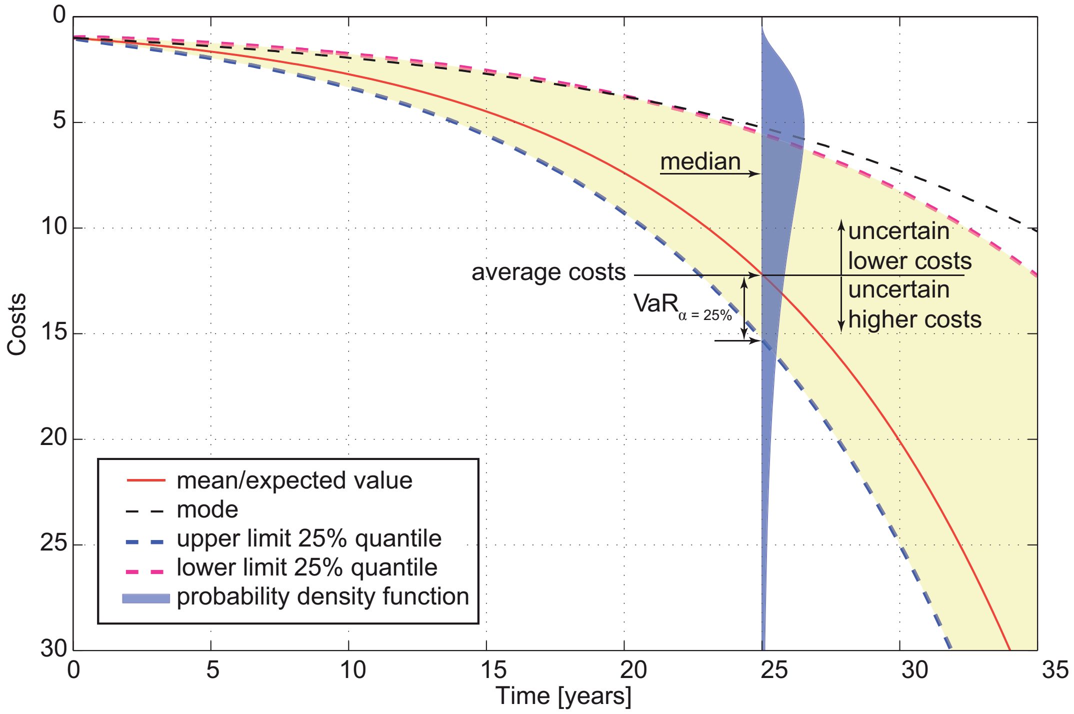


Figure 6: Illustration of a geometric Brownian motion process defining the magnitude of future costs for the parameters $\mu = 0.10$, $\sigma = 0.15$ and $S_0 = 1$.

In Fig. 6 the expected value depicted by the red line is (up to $t = 35$ years) surrounded by the upper and lower 25 percent quantile (dashed blue and red lines). The future costs' VaR is defined by the maximum deviation from the expected value occurring with the confidence level α.

$$\mathrm{VaR}_\alpha = \mathrm{CDF}_\alpha(t) - E(t) = \exp\left(\mu t - 0.5\sigma^2 t - \sigma\sqrt{2t}\,\mathrm{erf}(1-2\alpha)\right) - e^{\mu t} \tag{17}$$

Applying this definition, the VaR becomes zero for $\sigma = 0$, e.g. for the case of no uncertainty in the cash flow. For identifying the long-term characteristics of this value, the roots of equation (17) are evaluated, showing that VaR_α changes its sign at

$$t(\mathrm{VaR}_\alpha = 0) = \frac{8\ \mathrm{erf}(1-2\alpha)^2}{\sigma^2}. \tag{18}$$

At that particular point in time, the expected value is equal to the threshold value possibly occurring within the prescribed confidence level α. Consequently, for every chosen value of α, there is a time when the expected value of the future costs is higher than in the "worst-case" scenario, which seems to be implausible at first sight. However, the reason for this behavior is that the scenarios with extreme costs (although their probability of appearance is very low) influence the average value to a high extent due to the log-scaled probability density function. As the VaR increases initially like an exponential function in time, a graphical illustration of this value is for larger times impractical. Thus, we define a relative VaR such that

$$\begin{aligned} \mathrm{rVaR}_\alpha &= \frac{\mathrm{CDF}_\alpha(t) - E(t)}{E(t)} \\ &= 1 - \exp\left(-0.5\sigma^2 t - \sqrt{2t}\,\sigma\ \mathrm{erf}(1-2\alpha)\right), \end{aligned} \tag{19}$$

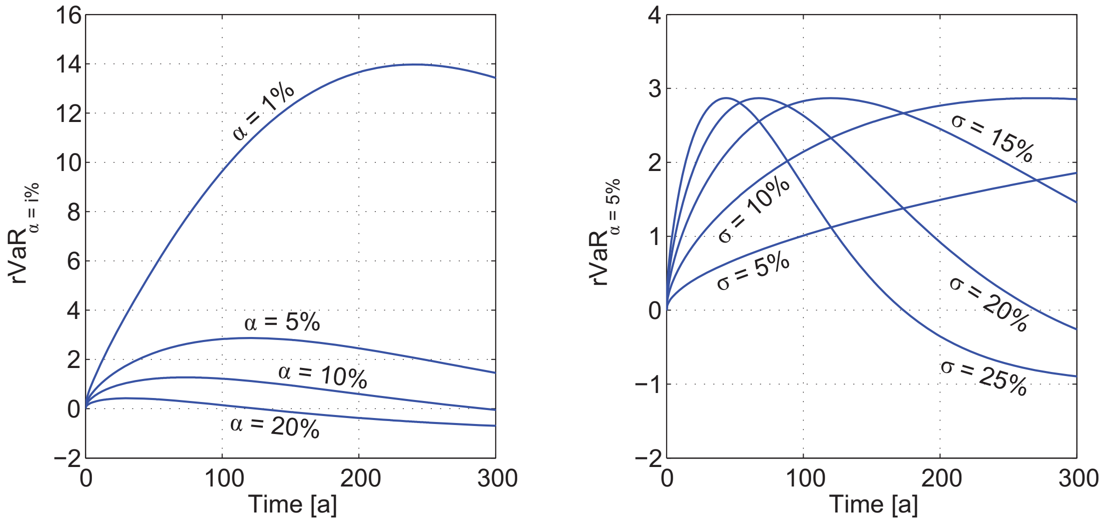
characterizes the ratio between the additional cost in a "worst-case" scenario and the expected costs. As can be seen from the equation above, this ratio is independent from the growth rate μ.

Figures 7(a) and 7(b) depict the influence of the confidence level α and the volatility σ on the relative VaR. As expected, the value grows initially over time, representing an increasing uncertainty of future costs. However, at the time

$$t(\mathrm{rVaR}_{\alpha,\max}) = \frac{2\ \mathrm{erf}(1-2\alpha)^2}{\sigma^2} \tag{20}$$

the relative VaR reaches its maximum, followed by a decrease of this risk measure. The time at which the maximum value occurs is $1/4 \cdot t(\mathrm{VaR}_\alpha = 0)$, see eq. (18). Note that the time horizon shown in the two graphs is as long as 300 years.

Varying the value of α shows an increase of the maximum rVaR with a decreasing confidence level α as well as an increase in $t(\mathrm{rVaR}_{\alpha,\max})$. Contrary, an increase in the volatility level σ leads to an earlier maximum as well as an earlier decay, whereas the maximal



(a) Variation of the confidence level α ($\sigma = 0.15$) (b) Variation of the volatility σ

Figure 7: Temporal development of the relative value at risk (rVaR) for the case of negative end-of-lifetime pay-offs.

relative VaR is not significantly influenced. From these findings, some quite astonishing conclusions can be drawn, such as for instance that the long-term risk of high volatile eternal cost is lower compared to the risk of low volatile eternal cost.

5 Conclusion

This paper critically discusses the risk inherent in ultra-long-lived investment projects implied if future pay-offs are assumed to follow a GBM process. The temporal development of the price defined by such a process is characterized by an exponential increase of the mean/expected value and a continuously increasing variance.

Distinguishing between projects with future revenues and future costs we compare the thresholds of the confidence levels of the uncertain cash flow's probability density function (also known as the value at risk) with the returns of a risk-free asset. The risk measure for both cases is found to develop entirely contrary to the variance when it comes to ultra-long-lived projects. For large time horizons, the lower confidence interval exceeds the returns of a risk-free asset for any choice of the confidence level. This means that for the case of revenues, the returns of a "worst-case" scenario (within the assumed confidence interval) will still exceed the returns of a risk-free asset also in the very long-term perspective. And, for the case of costs, the average costs will exceed the "worst-case" scenario's costs in the very long-term perspective. This rather extraordinary result is caused by the log-normal price distribution following from the GBM's development. Thus, from a modeling perspective, the choice of the GBM process and the results obtained have to be well scrutinized when it comes to the analysis of ultra-long-lived investment projects.

Furthermore, if the GBM process is assumed to be the proper choice for reflecting the value of future cash flows, the present results question the applicability of risk-adjusted discount rates, such as it is prescribed by the CAPM, for ultra-long-lived investments. Because of the vanishing risk in the long-term perspective, discount rates higher than the risk-free rate would mislead decision-makers, in that they neglect effects and cash flows of future periods due to their low weighting, resulting in a truncated planning horizon.

Nomenclature

Symbol	**Description**	**Acronym**	**Description**
α	confidence level	CAPM	capital asset pricing model
δ	discount rate	CDF	cumulative density function
μ	growth rate/drift	GBM	geometric Brownian motion
σ	volatility	NPV	net present value
r_f	risk-free discount rate	PDF	probability density function
t	time	RFA	risk-free asset
		RP	risk premium
		VaR	value at risk

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