Financial Risk Management
Lecture 11. Stress Testing and Scenario Analysis

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Overview
The objective of this course is to understand the theoretical and practical aspects of risk management

Prerequisites
M1 Finance or equivalent

ECTS
4

Keywords
Finance, Risk Management, Applied Mathematics, Statistics

Hours
Lectures: 36h, Training sessions: 15h, HomeWork: 30h

Evaluation
There will be a final three-hour exam, which is made up of questions and exercises

Course website
The objective of the course is twofold:

1. knowing and understanding the financial regulation (banking and others) and the international standards (especially the Basel Accords)
2. being proficient in risk measurement, including the mathematical tools and risk models
## Class schedule

### Course sessions
- September 11 (6 hours, AM+PM)
- September 18 (6 hours, AM+PM)
- September 25 (6 hours, AM+PM)
- October 2 (6 hours, AM+PM)
- November 20 (6 hours, AM+PM)
- November 27 (6 hours, AM+PM)

### Tutorial sessions
- October 10 (3 hours, AM)
- October 16 (3 hours, AM)
- November 13 (3 hours, AM)
- December 4 (6 hours, AM+PM)

Class times: Fridays 9:00am-12:00pm, 1:00pm–4:00pm, University of Evry
Agenda

- Lecture 1: Introduction to Financial Risk Management
- Lecture 2: Market Risk
- Lecture 3: Credit Risk
- Lecture 4: Counterparty Credit Risk and Collateral Risk
- Lecture 5: Operational Risk
- Lecture 6: Liquidity Risk
- Lecture 7: Asset Liability Management Risk
- Lecture 8: Model Risk
- Lecture 9: Copulas and Extreme Value Theory
- Lecture 10: Monte Carlo Simulation Methods
- Lecture 11: Stress Testing and Scenario Analysis
- Lecture 12: Credit Scoring Models
Additional materials

- Slides, tutorial exercises and past exams can be downloaded at the following address:
  

- Solutions of exercises can be found in the companion book, which can be downloaded at the following address:
  
Lecture 1: Introduction to Financial Risk Management
Lecture 2: Market Risk
Lecture 3: Credit Risk
Lecture 4: Counterparty Credit Risk and Collateral Risk
Lecture 5: Operational Risk
Lecture 6: Liquidity Risk
Lecture 7: Asset Liability Management Risk
Lecture 8: Model Risk
Lecture 9: Copulas and Extreme Value Theory
Lecture 10: Monte Carlo Simulation Methods
Lecture 11: Stress Testing and Scenario Analysis
Lecture 12: Credit Scoring Models
“Stress testing is now a critical element of risk management for banks and a core tool for banking supervisors and macroprudential authorities” (BCBS, 2017, page 5).
If we consider a trading book portfolio, we recall that:

\[ L_s (w) = P_t (w) - g (F_{1,s}, \ldots, F_{m,s}; w) \]

In the case of a stress testing program, we have:

\[ L_{\text{stress}} (w) = P_t (w) - g (F_{1,\text{stress}}, \ldots, F_{m,\text{stress}}; w) \]

where \((F_{1,\text{stress}}, \ldots, F_{m,\text{stress}})\) is the stress scenario
Scenario design and risk factors

2004 FSAP stress scenarios applied to the French banking system

- $F_1$: flattening of the yield curve due to an increase in interest rates: increase of 150 basis points (bp) in overnight rates, increase of 50 bp in 10-year rates, with interpolation for intermediate maturities

- $F_5$: share price decline of 30% in all stock markets

- $F_9$: flattening of the yield curve (increase of 150 basis points in overnight rates, increase of 50 bp in 10-year rates) together with a 30% drop in stock markets

- $M_2$: increase to USD 40 in the price per barrel of Brent crude for two years (an increase of 48% compared with USD 27 per barrel in the baseline case), without any reaction from the central bank; the increase in the price of oil leads to an increase in the general rate of inflation and a decline in economic activity in France together with a drop in global demand
Classification

1. historical scenario: “a stress test scenario that aims at replicating the changes in risk factor shocks that took place in an actual past episode”

2. hypothetical scenario: “a stress test scenario consisting of a hypothetical set of risk factor changes, which does not aim to replicate a historical episode of distress”

3. macroeconomic scenario: “a stress test that implements a link between stressed macroeconomic factors [...] and the financial sustainability of either a single financial institution or the entire financial system”

4. liquidity scenario: “a liquidity stress test is the process of assessing the impact of an adverse scenario on institution's cash flows as well as on the availability of funding sources, and on market prices of liquid assets”
Scenario design and risk factors

Figure: 2017 DFAST supervisory scenarios: Domestic variables
Scenario design and risk factors

Figure: 2017 DFAST supervisory scenarios: International variables
Firm-specific versus supervisory stress testing

Examples of hard trading limits:
- Unobservable parameters (e.g. correlations of basket options)
- Less liquid assets

Examples of supervisory stress testing:
- Financial sector assessment program (FSAP)
- Dodd-Frank Act stress test (DFAST)
- EU-wide stress testing
### Historical approach

**Table:** Worst historical scenarios of the S&P 500 index

<table>
<thead>
<tr>
<th>Sc.</th>
<th>1D</th>
<th>1W</th>
<th>1M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1987-10-19</td>
<td>−20.47</td>
<td>1987-10-19</td>
</tr>
<tr>
<td>2</td>
<td>2008-10-15</td>
<td>−9.03</td>
<td>2008-10-09</td>
</tr>
<tr>
<td>3</td>
<td>2008-12-01</td>
<td>−8.93</td>
<td>2008-11-20</td>
</tr>
<tr>
<td>5</td>
<td>1987-10-26</td>
<td>−8.28</td>
<td>2011-08-08</td>
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</table>

<table>
<thead>
<tr>
<th>Sc.</th>
<th>2M</th>
<th>3M</th>
<th>6M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2008-11-20</td>
<td>−37.66</td>
<td>2008-11-20</td>
</tr>
<tr>
<td>2</td>
<td>1987-10-26</td>
<td>−31.95</td>
<td>1987-11-30</td>
</tr>
<tr>
<td>3</td>
<td>2002-07-23</td>
<td>−27.29</td>
<td>1974-09-13</td>
</tr>
</tbody>
</table>
Macro-economic approach

Exogenous Shock → Model → Risk Factors

**Figure:** Macroeconomic approach of stress testing
Macro-economic approach

Figure: Feedback effects in stress testing models
At first approximation, a stress scenario can be seen as an extreme quantile or value-at-risk ⇒ we can use EVT (extreme value theory)
Univariate stress scenarios

- Let $X$ be the random variable that produces the stress scenario $\mathcal{S}(X)$. If $X \sim F$ and the relationship between $L(w)$ and $X$ is decreasing, we have:

  $$\Pr \{X \leq \mathcal{S}(X)\} = F(\mathcal{S}(X))$$

- Given a stress scenario $\mathcal{S}(X)$, we deduce its severity:

  $$\alpha = F(\mathcal{S}(X))$$

- We can also compute the stressed value given the probability of occurrence $\alpha$:

  $$\mathcal{S}(X) = F^{-1}(\alpha)$$

  $$\alpha \approx 0 \ (\neq \text{value-at-risk})$$
Univariate stress scenarios

Return time

- We have $T = \alpha^{-1}$ and $\alpha = T^{-1}$
- We reiterate that:

$$T = \alpha^{-1} = n \cdot (1 - \alpha_{GEV})^{-1}$$

where $n$ is the length of the block maxima

Table: Probability (in %) associated to the return period $T$ in years

<table>
<thead>
<tr>
<th>Return period</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily</td>
<td>0.3846</td>
<td>0.0769</td>
<td>0.0385</td>
<td>0.0192</td>
<td>0.0128</td>
<td>0.0077</td>
</tr>
<tr>
<td>Weekly</td>
<td>1.9231</td>
<td>0.3846</td>
<td>0.1923</td>
<td>0.0962</td>
<td>0.0641</td>
<td>0.0385</td>
</tr>
<tr>
<td>Monthly</td>
<td>8.3333</td>
<td>1.6667</td>
<td>0.8333</td>
<td>0.4167</td>
<td>0.2778</td>
<td>0.1667</td>
</tr>
<tr>
<td>$1 - \alpha_{GEV}$</td>
<td>7.6923</td>
<td>1.5385</td>
<td>0.7692</td>
<td>0.3846</td>
<td>0.2564</td>
<td>0.1538</td>
</tr>
</tbody>
</table>
Univariate stress scenarios

Table: GEV parameter estimates (in %) of MSCI USA and MSCI EMU indices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Long position</th>
<th>Short position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSCI USA</td>
<td>MSCI EMU</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1.242</td>
<td>1.572</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.720</td>
<td>0.844</td>
</tr>
</tbody>
</table>
### Univariate stress scenarios

Table: Stress scenarios (in %) of MSCI USA and MSCI EMU indices

<table>
<thead>
<tr>
<th>Year</th>
<th>Long position</th>
<th>Short position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSCI USA</td>
<td>MSCI EMU</td>
</tr>
<tr>
<td>5</td>
<td>-5.86</td>
<td>-7.27</td>
</tr>
<tr>
<td>10</td>
<td>-7.06</td>
<td>-8.83</td>
</tr>
<tr>
<td>25</td>
<td>-8.92</td>
<td>-11.29</td>
</tr>
<tr>
<td>50</td>
<td>-10.56</td>
<td>-13.49</td>
</tr>
<tr>
<td>75</td>
<td>-11.62</td>
<td>-14.94</td>
</tr>
<tr>
<td>100</td>
<td>-12.43</td>
<td>-16.05</td>
</tr>
<tr>
<td>Extreme statistic</td>
<td>-9.51</td>
<td>-10.94</td>
</tr>
<tr>
<td>$T^*$</td>
<td>32.49</td>
<td>22.24</td>
</tr>
</tbody>
</table>
Univariate stress scenarios

Figure: Stress scenarios (in %) of MSCI USA and MSCI EMU indices
Bivariate stress scenarios

- We note $p = \Pr \{X_{n:n,1} > S(X_1), X_{n:n,2} > S(X_2)\}$ the joint probability of stress scenarios $(S(X_1), S(X_2))$
- We have:

$$p = 1 - F_1(S(X_1)) - F_2(S(X_2)) + C(F_1(S(X_1)), F_2(S(X_2)))$$

$$= \bar{\C}(F_1(S(X_1)), F_2(S(X_2)))$$

where $\bar{\C}(u_1, u_2) = 1 - u_1 - u_2 + C(u_1, u_2)$
- We deduce that the failure area is represented by:

$$\left\{ (S(X_1), S(X_2)) \in \mathbb{R}_2^+ \mid \bar{\C}(F_1(S(X_1)), F_2(S(X_2))) \leq \frac{n}{T} \right\}$$

- We have:

$$T = \frac{n}{\bar{\C}(F_1(S(X_1)), F_2(S(X_2)))}$$

and:

$$\max(T_1, T_2) \leq T \leq nT_1T_2$$
Bivariate stress scenarios

Figure: Failure area of MSCI USA and MSCI EMU indices (blockwise dependence)
Bivariate stress scenarios

Figure: Failure area of MSCI USA and MSCI EMU indices (daily dependence)
\[ \bar{C} \text{ has a complicated expression (see HFRM, Section 14.2.2.2, page 908)} \]
The conditional expectation solution

Given a joint stress scenario $\mathcal{S}(X) = (\mathcal{S}(X_1), \ldots, \mathcal{S}(X_n))$, the conditional stress scenario of $Y$ is:

$$
\mathcal{S}(Y) = \mathbb{E}[Y_t \mid X_t = (\mathcal{S}(X_1), \ldots, \mathcal{S}(X_n))] = \beta_0 + \sum_{i=1}^{n} \beta_i \mathcal{S}(X_i)
$$
The conditional expectation solution

Logit transformation

- We use the following transformation:

\[ Z_t = \ln \left( \frac{Y_t}{1 - Y_t} \right) \]

- We have:

\[ Y_t = \frac{\exp(Z_t)}{1 + \exp(Z_t)} = \frac{1}{1 + \exp(-Z_t)} = h(Z_t) \]

where \( h(z) \) is the logit transformation

- We deduce that:

\[
\mathbb{E} [Y_t \mid X_t = (x_1, \ldots, x_n)] = \int_{-\infty}^{\infty} h \left( \beta_0 + \sum_{i=1}^{n} \beta_i X_{i,t} + \omega \right) \frac{1}{\sigma} \phi \left( \frac{\omega}{\sigma} \right) \, d\omega
\]
The conditional expectation solution

Example

- We assume that the probability of default $PD_t$ at time $t$ is explained by the following linear regression model:

$$\ln \left( \frac{PD_t}{1 - PD_t} \right) = -2.5 - 5g_t - 3\pi_t + 2u_t + \varepsilon_t$$

where $\varepsilon_t \sim \mathcal{N}(0, 0.25)$, $g_t$ is the growth rate of the GDP, $\pi_t$ is the inflation rate, and $u_t$ is the unemployment rate.

- The baseline scenario is defined by $g_t = 2\%$, $\pi_t = 2\%$ and $u_t = 5\%$

- The stress scenario is equal to $g_t = -8\%$, $\pi_t = 5\%$ and $u_t = 10\%$
The conditional expectation solution

**Figure:** Probability density function of $\text{PD}_t$
The conditional expectation solution

⇒ The conditional expectation is equal to 7.90% for the baseline scenario and 12.36% for the stress scenario.

⇒ The figure of 7.90% can be interpreted as the long-run (or unconditional) probability of default that is used in the IRB formula (i.e. Pillar I).

⇒ The figure of 12.36% may be used in Pillar II.
The conditional expectation solution

Figure: Relationship between the macroeconomic variables and $\text{PD}_t$
The conditional expectation solution

**Table:** Stress scenario of the probability of default

<table>
<thead>
<tr>
<th>$t$</th>
<th>$g_t$</th>
<th>$\pi_t$</th>
<th>$u_t$</th>
<th>$\mathbb{E}[PD_t \mid S(X)]$</th>
<th>$q_{090%}(S(X))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.00</td>
<td>2.00</td>
<td>5.00</td>
<td>7.90</td>
<td>12.78</td>
</tr>
<tr>
<td>1</td>
<td>-6.00</td>
<td>2.00</td>
<td>6.00</td>
<td>11.45</td>
<td>18.26</td>
</tr>
<tr>
<td>2</td>
<td>-7.00</td>
<td>1.00</td>
<td>7.00</td>
<td>12.47</td>
<td>19.79</td>
</tr>
<tr>
<td>3</td>
<td>-9.00</td>
<td>1.00</td>
<td>9.00</td>
<td>14.03</td>
<td>22.14</td>
</tr>
<tr>
<td>4</td>
<td>-7.00</td>
<td>1.00</td>
<td>10.00</td>
<td>13.12</td>
<td>20.78</td>
</tr>
<tr>
<td>5</td>
<td>-7.00</td>
<td>2.00</td>
<td>11.00</td>
<td>13.01</td>
<td>20.59</td>
</tr>
<tr>
<td>6</td>
<td>-6.00</td>
<td>2.00</td>
<td>10.00</td>
<td>12.26</td>
<td>19.49</td>
</tr>
<tr>
<td>7</td>
<td>-4.00</td>
<td>4.00</td>
<td>9.00</td>
<td>10.49</td>
<td>16.80</td>
</tr>
<tr>
<td>8</td>
<td>-2.00</td>
<td>3.00</td>
<td>8.00</td>
<td>9.70</td>
<td>15.58</td>
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<td>9</td>
<td>-1.00</td>
<td>3.00</td>
<td>7.00</td>
<td>9.11</td>
<td>14.68</td>
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<td>10</td>
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<td>3.00</td>
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<td>7.82</td>
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<tr>
<td>11</td>
<td>4.00</td>
<td>3.00</td>
<td>6.00</td>
<td>7.14</td>
<td>11.60</td>
</tr>
<tr>
<td>12</td>
<td>4.00</td>
<td>3.00</td>
<td>6.00</td>
<td>7.14</td>
<td>11.60</td>
</tr>
</tbody>
</table>
The conditional quantile solution

We could also define the conditional stress scenario $S(Y) = q_\alpha (S(X))$ as the solution of the quantile regression:

$$\Pr \{ Y_t \leq q_\alpha (S) \mid X_t = S \} = \alpha$$

The solution is given by:

$$S(Y) = q_\alpha (S) = F^{-1}_y \left( C_{2|1}^{-1} (F_x (S(X)), \alpha) \right)$$

⇒ See HFRM, Section 14.2.3.2, pages 912-915
Reverse stress testing

Reverse stress test “means an institution stress test that starts from the identification of the pre-defined outcome (e.g. points at which an institution business model becomes unviable, or at which the institution can be considered as failing or likely to fail) and then explores scenarios and circumstances that might cause this to occur”

- In stress testing, extreme scenarios of risk factors are used to test the viability of the bank:

\[
(\mathcal{S}(F_1), \ldots, \mathcal{S}(F_m)) \Rightarrow \mathcal{S}(L(w)) \Rightarrow \begin{cases} D = 0 & \text{if } \mathcal{S}(L(w)) < C \\ D = 1 & \text{otherwise} \end{cases}
\]

- In reverse stress testing, extreme scenarios of risk factors are deduced from the bankruptcy scenario:

\[
D = 1 \Rightarrow \mathcal{RS}(L(w)) \Rightarrow (\mathcal{RS}(F_1), \ldots, \mathcal{RS}(F_m))
\]
Reverse stress testing

We recall that:

\[ L(w) = \ell(F_1, \ldots, F_m; w) \]

The reverse stress scenario \( RS \) is the set of risk factors that corresponds to the stressed loss \( RS(L(w)) \):

\[ RS = \{ (RS(F_1), \ldots, RS(F_m)) : \ell(S(F_1), \ldots, S(F_m); w) = RS(L(w)) \} \]

\( \Rightarrow \) Not a unique solution

Mathematical solution

We can use the following optimization program

\[
(RS(F_1), \ldots, RS(F_m)) = \arg \max \ln f(F_1, \ldots, F_m)
\]

s.t. \( \ell(S(F_1), \ldots, S(F_m); w) = RS(L(w)) \)

where \( f(x_1, \ldots, x_m) \) is the probability density function of the risk factors \( (F_1, \ldots, F_m) \)
Reverse stress testing

We assume that $\mathcal{F} \sim \mathcal{N}(\mu_\mathcal{F}, \Sigma_\mathcal{F})$ and $L(w) = \sum_{j=1}^m w_j \mathcal{F}_j = w^\top \mathcal{F}$. The optimization problem becomes:

$$\text{RS}(\mathcal{F}) = \arg \min \frac{1}{2} (\mathcal{F} - \mu_\mathcal{F})^\top \Sigma_\mathcal{F}^{-1} (\mathcal{F} - \mu_\mathcal{F})$$

s.t. $w^\top \mathcal{F} = \text{RS}(L(w))$

The Lagrange function is:

$$\mathcal{L}(\mathcal{F}; \lambda) = \frac{1}{2} (\mathcal{F} - \mu_\mathcal{F})^\top \Sigma_\mathcal{F}^{-1} (\mathcal{F} - \mu_\mathcal{F}) - \lambda (w^\top \mathcal{F} - \text{RS}(L(w)))$$

The first-order condition is $\Sigma_\mathcal{F}^{-1} (\mathcal{F} - \mu_\mathcal{F}) - \lambda w = 0$. It follows that $\mathcal{F} = \mu_\mathcal{F} + \lambda \Sigma_\mathcal{F} w$, $w^\top \mathcal{F} = w^\top \mu_\mathcal{F} + \lambda w^\top \Sigma_\mathcal{F} w$, $\lambda = (\text{RS}(L(w)) - w^\top \mu_\mathcal{F}) / w^\top \Sigma_\mathcal{F} w$ and:

$$\text{RS}(\mathcal{F}) = \mu_\mathcal{F} + \frac{\Sigma_\mathcal{F} w}{w^\top \Sigma_\mathcal{F} w} (\text{RS}(L(w)) - w^\top \mu_\mathcal{F})$$
Reverse stress testing

Another approach for solving the inverse problem is to consider the joint distribution of $\mathcal{F}$ and $L(w)$:

$$
\begin{pmatrix}
\mathcal{F} \\
L(w)
\end{pmatrix}
\sim
\mathcal{N}
\left( 
\begin{pmatrix}
\mu_{\mathcal{F}} \\
w^\top \mu_{\mathcal{F}}
\end{pmatrix},
\begin{pmatrix}
\Sigma_{\mathcal{F}} & \Sigma_{\mathcal{F}}w \\
w^\top \Sigma_{\mathcal{F}} & w^\top \Sigma_{\mathcal{F}} w
\end{pmatrix}
\right)
$$

The conditional distribution of $\mathcal{F}$ given $L(w) = \text{RS}(L(w))$ is Gaussian:

$$
\mathcal{F} \mid L(w) = \text{RS}(L(w)) \sim \mathcal{N}(\mu_{\mathcal{F} \mid L(w)}, \Sigma_{\mathcal{F} \mid L(w)})
$$

We know that the maximum of the probability density function of the multivariate normal distribution is reached when the random vector is exactly equal to the mean. We deduce that:

$$
\text{RS}(\mathcal{F}) = \mu_{\mathcal{F} \mid L(w)} = \mu_{\mathcal{F}} + \frac{\Sigma_{\mathcal{F}} w}{w^\top \Sigma_{\mathcal{F}} w} \left( \text{RS}(L(w)) - w^\top \mu_{\mathcal{F}} \right)
$$
Reverse stress testing

Example

We assume that $\mathcal{F} = (\mathcal{F}_1, \mathcal{F}_2)$, $\mu_\mathcal{F} = (5, 8)$, $\sigma_\mathcal{F} = (1.5, 3.0)$ and $\rho(\mathcal{F}_1, \mathcal{F}_2) = -50\%$. The sensitivity vector $w$ to the risk factors is equal to $(10, 3)$

The stress scenario is the collection of univariate stress scenarios at the 99% confidence level:

\[
\begin{align*}
S(\mathcal{F}_1) &= 5 + 1.5 \cdot \Phi^{-1}(99\%) = 8.49 \\
S(\mathcal{F}_2) &= 8 + 3.0 \cdot \Phi^{-1}(99\%) = 14.98
\end{align*}
\]

The stressed loss is then equal to:

\[
S(L(w)) = 10 \cdot 8.49 + 3 \cdot 14.98 = 129.53
\]
Reverse stress testing

We assume that the reverse stressed loss is equal to 129.53 ⇒ we deduce that $RS(F_1) = 10.14$ and $RS(F_2) = 9.47$

Remark

The reverse stress scenario is very different than the stress scenario even if they give the same loss. In fact, we have $f(S(F_1), S(F_2)) = 0.8135 \cdot 10^{-6}$ and $f(RS(F_1), RS(F_2)) = 4.4935 \cdot 10^{-6}$, meaning that the occurrence probability of the reverse stress scenario is more than five times higher than the occurrence probability of the stress scenario.
Reverse stress testing

In the general case, we consider the following optimization problem:

\[
\begin{align*}
(\mathcal{RS}(\mathcal{F}_1), \ldots, \mathcal{RS}(\mathcal{F}_m)) &= \arg \max \ln f(\mathcal{F}_1, \ldots, \mathcal{F}_m) \\
\text{s.t.} \quad \ell(\mathcal{S}(\mathcal{F}_1), \ldots, \mathcal{S}(\mathcal{F}_m); w) &\geq \mathcal{RS}(\mathcal{L}(w))
\end{align*}
\]

and we use the Monte Carlo simulation method to estimate the reverse stress scenario

**Hard to implement in practice!**
Exercise 14.3.1 – Construction of a stress scenario with the GEV distribution
References

- Basel Committee on Banking Supervision (2017)

- Roncalli, T. (2020)
  Handbook of Financial Risk Management, Chapman and Hall/CRC
  Financial Mathematics Series, Chapter 14.

- Roncalli, T. (2020)
  Handbook of Financial Risk Management – Companion Book,
  Chapter 14.