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Coherent measures of risk
P Artzner, F Delbaen, JM Eber... - *Mathematical finance*, 1999 - Wiley Online Library
Mathematical Finance, Vol. ... KEY WORDS: aggregation of risks, butterfly, capital requirement, coherent risk measure, concentration of risks, currency risk ... extremal events risk, insurance risk, margin requirement, market risk, mean excess function, measure of risk, model risk, net ...
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On the assessment of risk
ME Burne - *The Journal of Finance*, 1971 - JSTOR
... for the same portfolio estimated in the next period.²⁰ The risk measure calculated using the ... of unexplained variation may make the beta coefficient an inadequate measure of risk for analyzing the ... The Journal of Finance TABLE 3 Estimated BETA Coefficients for Portfolios of 100 ...
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[PDF] Optimization of conditional value-at-risk
RT Rockafellar... - *Journal of risk*, 2000 - Citeseer
... As an alternative measure of risk, CVaR is known to have better properties than VaR, see Artzner et al. ... Recently, Pflug (2000) proved that CVaR is a coherent risk measure ... has not become a standard in the finance industry. CVaR is gaining in the insurance industry. ...
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Spectral measures of risk: a coherent representation of subjective risk aversion
C Acerbi - *Journal of Banking & Finance*, 2002 - Elsevier
... *Journal of Banking & Finance* Volume 26, Issue 7, July 2002. Pages 1505-1518. ... et al., 1997 and Artzner et al., 1999 where the notion of coherent measure of risk was introduced ... and Lauprete (2000), where the introduction of expected shortfall as a risk measure was motivated ...
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Convex measures of risk and trading constraints
H Föllmer... - *Finance and Stochastics*, 2002 - Springer
Page 1. *Finance Stochast.* 6, 429-447 (2002) © Springer-Verlag 2002 Convex measures of risk and trading constraints ... Abstract. We introduce the notion of a convex measure of risk, an extension of the concept of a coherent risk measure defined in Artzner et al. ...
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The Marginal Cost of Risk, Risk Measures, and Capital Allocation

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The Capital Allocation Problem

Auto (Risk 1)

I_1

Property (Risk 2)

I_2

Workers Comp (Risk 3)

I_3

The Capital Allocation Problem

Auto (Risk 1)

I_1

Property (Risk 2)

I_2

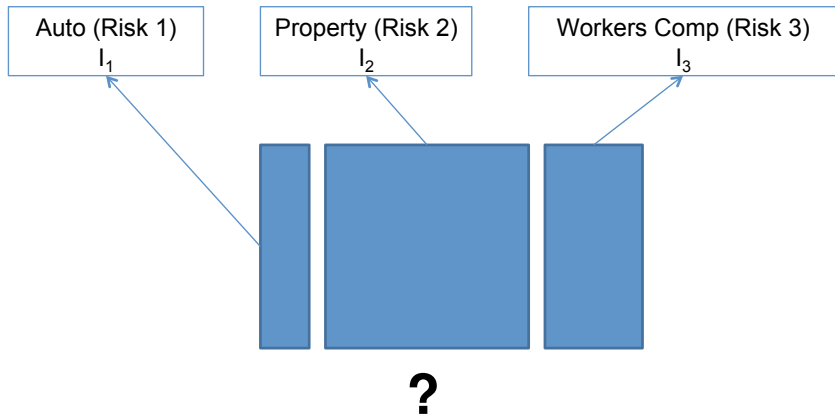
Workers Comp (Risk 3)

I_3

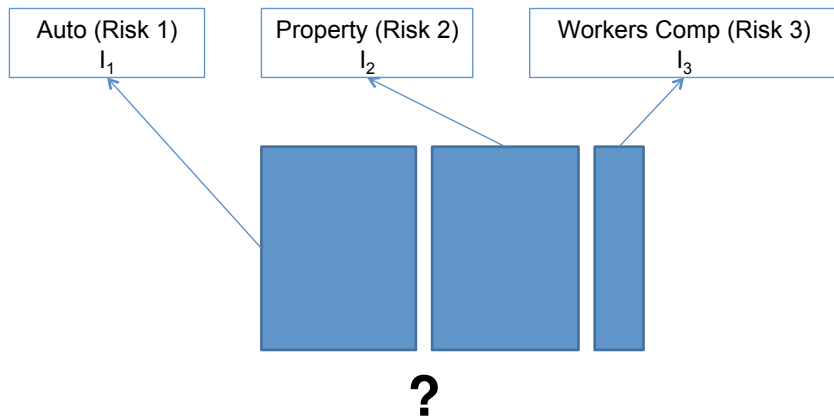


Capital

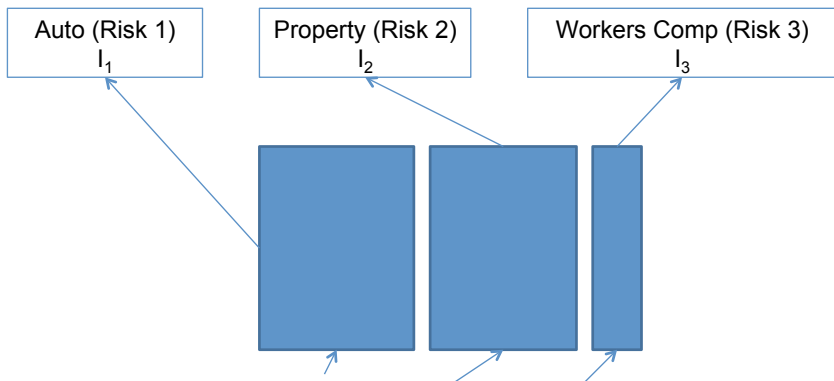
The Capital Allocation Problem



The Capital Allocation Problem



The Capital Allocation Problem



$$\frac{\partial \rho(l)}{\partial q_1} \times q_1 + \frac{\partial \rho(l)}{\partial q_2} \times q_2 + \frac{\partial \rho(l)}{\partial q_3} \times q_3 = a,$$

... where $a = \rho(l)$, $l = l_1 + l_2 + l_3$ and $l_i = q_i \times L_i$

- Easy to implement, billed as economic (connection to marginal cost)
- So: [(1) Choose $\rho \Rightarrow$ (2) Allocate Capital] – but **how to choose ρ ?**

What we do: The opposite



Our approach

We start with a primitive economic model of profit maximizing insurer, calculate marginal cost and the implied capital allocation, and then figure out what risk measure would yield the correct allocation

Economic Model \Rightarrow Marginal Cost \Rightarrow Capital Allocation \Rightarrow Risk Measure

Preview of Results

- ▶ Study profit maximizing insurer with risk averse counterparties, facing a (possibly non-binding) regulatory capital constraint.

Thus, there are three sources of “discipline” – (1) the regulator (via risk measure s), (2) shareholders’ access to future profits, and (3) counterparties that determine capital allocation:

$$\lambda_1 \times \left[\frac{\partial s(l)}{\partial q_i} \right] + \lambda_2 \times \left[\tilde{\theta}_i \right] \times + (1 - (\lambda_1 + \lambda_2)) \times \left[\tilde{\phi}_i \right]$$

↙
↓
↘

(1)
(2)
(3)

- ▶ "Going concern" allocation $\tilde{\theta}_i$ is determined via gradient of Value-at-Risk:

$$\tilde{\theta}_i = \frac{\partial}{\partial q_i} \text{VaR}_{\alpha^*}(l)$$

Preview of Results

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(1)
(2)
(3)

- ▶ "Going concern" allocation $\tilde{\theta}_i$ is determined via gradient of Value-at-Risk:

$$\tilde{\theta}_i = \frac{\partial}{\partial q_i} \text{VaR}_{\alpha^*}(l)$$

- ▶ "Counterparty-driven" allocation $\tilde{\phi}_i$ is determined via gradient of "new" risk measure $\tilde{\rho}$:

$$\tilde{\phi}_i = \frac{\partial \tilde{\rho}(l)}{\partial q_i} \text{ where } \tilde{\rho}(X) = \exp \left\{ \mathbb{E}^{\tilde{\mathbb{P}}} [\log \{X\}] \right\}$$

Preview of Results (2)

- ▶ $\tilde{\rho}$ is **neither convex nor coherent** due to embedded log-transformation
 - Stems from "**limited liability**" – extreme states less important since there is not much left to share
- ▶ But includes an absolutely continuous measure transformation $\frac{\partial \tilde{\mathbb{P}}}{\partial \mathbb{P}}$ that
 - ▶ keeps the **focus on the default states**, i.e. $\tilde{\mathbb{P}}(I \geq a) = 1$
 - ▶ **depends on the consumers' marginal utilities in loss states**, which are higher in extreme states
- ▶ In a setting with security markets, result pertains in the "branch" where market becomes incomplete
 - ▶ In limiting case of completeness, results in Ibragimov et al. (2010) allocation
- ▶ For $X = I$, we can represent $\bar{\rho}(I) = \exp \{ \mathbb{E} [\psi(I) \log \{ I \} | I \geq a] \}$
 - ▶ Relationship to *Spectral Risk Measure* (Acerbi, 2002)
 - ▶ For homogeneous exponential losses and CARA utility (ARA a , N risks):

$$\psi(I) = \text{const} \times \mathbf{1}_{\{I \geq a\}} \times \sum_{k=0}^{\infty} \frac{(k+1)(\alpha(I-a))^k}{(N+k)!}$$
 - ▶ In comparison to other allocation methods (here CTE), results may be more or less conservative, depending on e.g. expected loss and risk aversion

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Basic Model Setup (one period model without security market)

- ▶ Consumer i faces loss L_i (non-negative random variable)
 - ▶ Firm determines optimal **asset** level a , optimal coverage **indemnification level**, which is given by $l_i = l_i(L_i, q_i)$ with choice parameter q_i , $l = \sum l_i$, and optimal **premium** level p_i
 - ▶ In non-default states, consumer gets full indemnification amount. In default states, all claimants are paid at the same rate per dollar of coverage
- Recovery $R_i = \min \{ l_i, \frac{a}{l} l_i \}$ with expected value

$$e_i = \mathbb{E}[R_i] = \underbrace{\mathbb{E}[R_i \mathbf{1}_{\{l < a\}}]}_{e_i^Z} + \underbrace{\mathbb{E}[R_i \mathbf{1}_{\{l \geq a\}}]}_{e_i^D}$$

- ▶ Tax on assets ($\tau \times a$)
- ▶ Consumer i with wealth level w_i has utility function U_i with

$$v_i = \mathbb{E}[U_i(w_i - p_i - L_i + R_i)]$$

► Firm solves

$$\begin{cases} \max_{a, \{p_i\}, \{q_i\}} \sum p_i - \sum e_i - \tau \times a \\ \text{s.th.} \\ v_i \geq \gamma_i, i = 1, \dots, N \quad (\text{participation constraint}) \\ s(q_1, \dots, q_n) \leq a \quad (\text{external solvency constraint}) \end{cases}$$

⇒ Under certain assumptions, optimal solution can be implemented by a monotonic premium schedule $p^*(\cdot)$ that satisfies

$$\frac{\partial p_i^*}{\partial q_i} = \underbrace{\frac{\partial e_i^Z}{\partial q_i}}_{\text{Extra claims cost to consumer } i} + \underbrace{\frac{\partial s}{\partial q_i} \left[\mathbb{P}(I \geq a) + \tau - \sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} \right]}_{\text{Cost relating to regulatory constraint}}$$

Extra claims cost
to consumer i

Cost relating to
regulatory constraint

$$+ \underbrace{\frac{\mathbb{E} \left[\frac{\frac{\partial I_i}{\partial q_i}}{I} \sum_k \frac{U'_k}{v'_k} \frac{I_k}{I} \mid I \geq a \right]}{\mathbb{E} \left[\sum_k \frac{U'_k}{v'_k} \frac{I_k}{I} \mid I \geq a \right]}}_{\tilde{\phi}_i} \times \sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} \times a$$

Cost relating to externalities
on other consumers

From Marginal Cost to Capital Allocation

- ▶ Marginal cost implies allocation of capital:

$$\frac{\partial p_i^*}{\partial q_i} = \frac{\partial e_i^Z}{\partial q_i} + \underbrace{\frac{\partial s}{\partial q_i} \left[\mathbb{P}(I \geq a) + \tau - \sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} \right]}_{\text{Regulator driven allocation}} + \underbrace{\tilde{\phi}_i \times \sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} \times a}_{\text{Counterparty driven allocation}}$$

- ▶ Why are we calling it an allocation?

$$\sum_i \frac{\partial p_i^*}{\partial q_i} \times q_i = e_i^Z + [\mathbb{P}(I \geq a) a + \tau a]$$

- ▶ Additional terms in multi-period model:

$$\underbrace{\frac{\partial s}{\partial q_i} \left[\mathbb{P}(I \geq a) + \tau - \sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} - V f_i(a) \right]}_{\text{Regulator driven allocation}} + \underbrace{\tilde{\phi}_i \times \sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} \times a}_{\text{Counterparty driven allocation}} + \underbrace{\mathbb{E} \left[\frac{\partial I}{\partial q_i} \mid I = a \right] \times V f_i(a) \times a}_{\text{Shareholder driven allocation } (\tilde{\theta}_i)}$$

- ▶ State prices enter when considering security market, but result pertains in "branch" where market becomes incomplete

Special Cases:

$$\frac{\partial s}{\partial q_i} \underbrace{\left[1 - \frac{\sum_k \frac{\frac{\partial v_k}{\partial a}}{v_k}}{\mathbb{P}(I \geq a) + \tau} - \frac{V f_i(a)}{\mathbb{P}(I \geq a) + \tau} \right]}_{\text{Regulator driven allocation}} + \underbrace{\tilde{\phi}_i \times a \times \left[\frac{\sum_k \frac{\frac{\partial v_k}{\partial a}}{v_k}}{\mathbb{P}(I \geq a) + \tau} \right]}_{\text{Counterparty driven allocation}} + \underbrace{\tilde{\theta}_i \times a \times \left[\frac{V f_i(a)}{\mathbb{P}(I \geq a) + \tau} \right]}_{\text{Shareholder driven allocation}}$$

- ▶ Full deposit insurance and perfect competition: $\lambda_1 = \lambda_2 = 0$ and allocation solely determined by **externally specified risk measure**
 - ▶ World of Myers and Read (2001), Tasche (2004) etc.
- ▶ Full deposit insurance, no or non-binding regulation, and monopolistic competition: $\lambda_1 = 0, \lambda_2 = 1$ – only $\tilde{\theta}_i$ matters, which derives as the gradient of **Value-at-Risk**
 - ▶ May explain popularity of VaR (deposit insurance prevalent)
- ▶ Competition and no regulation: $\lambda_1 = 1, \lambda_2 = 0$ – only $\tilde{\phi}_i$ matters, which is driven by counterparty risk aversion

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A Novel Risk Measure

- ▶ Regulator-driven allocation based on external risk measure, shareholder-driven allocation based on VaR
- ▶ **But what about counterparty-driven allocation?**

A Novel Risk Measure

- ▶ Regulator-driven allocation based on external risk measure, shareholder-driven allocation based on VaR
- ▶ **But what about counterparty-driven allocation?**

1. Define the probability measure $\tilde{\mathbb{P}}$ by the Radon-Nikodym derivative

$$\frac{\partial \tilde{\mathbb{P}}}{\partial \mathbb{P}} = \frac{\mathbf{1}_{\{I \geq a\}} \sum_k \frac{U'_k I_k}{v'_k I}}{\mathbb{E} \left[\mathbf{1}_{\{I \geq a\}} \sum_k \frac{U'_k I_k}{v'_k I} \right]}$$

- ▶ $\tilde{\mathbb{P}}$ absolutely continuous with respect to \mathbb{P} with $\tilde{\mathbb{P}}(I \geq a) = 1$

2. On $L^2_+ = \{X \in (\Omega, \mathcal{F}, \tilde{\mathbb{P}}) | X > 0\}$, define the **risk measure**

$$\tilde{\rho}(X) = \exp \left\{ \mathbb{E}^{\tilde{\mathbb{P}}} [\log \{X\}] \right\}$$

- ▶ While $\tilde{\rho}$ is monotonic, homogenous, and satisfies constancy, it is **not translation-invariant** and **not sub-additive**, and therefore **not coherent** and **not convex**
- ▶ However, it is correct for internal allocation according to the Euler principle...

The Euler Principle Revisited: No Deposit Insurance/No Regulation/One-Period

- Define $\tilde{\chi}_\rho = \frac{a^*}{\tilde{\rho}(I^*)}$ as the "exchange rate" between capital and risk. Then

$$\begin{cases} \pi(q_1, \dots, q_N, a) \rightarrow \max \\ \tilde{\rho}(q_1, \dots, q_N) \tilde{\chi}_\rho \leq a \end{cases}$$

yields allocation

$$\begin{aligned} \sum_k \tilde{\chi}_\rho \frac{\partial \tilde{\rho}}{\partial q_k} q_k^* \underbrace{\left(-\frac{\partial \pi}{\partial a} \right)}_{\mathbb{P}(I \geq a^*) + \tau} &= \sum_k \tilde{\phi}_k q_k^* a^* [\mathbb{P}(I \geq a^*) + \tau] \\ &= a^* [\mathbb{P}(I \geq a^*) + \tau] \\ \implies \sum_k \tilde{\chi}_\rho \frac{\partial \tilde{\rho}}{\partial q_k} q_k^* &= a^* \end{aligned}$$

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- \implies Capital allocation can be implemented by differentiating **novel risk measure** at current portfolio

The Euler Principle Revisited: General Case

- Here we have two restrictions: ($\alpha^* = \mathbb{P}(I^* \leq a^*)$)

$$\begin{cases} \pi^{1\text{per.}}(q_1, \dots, q_N, a) \rightarrow \max \\ s(q_1, \dots, q_N) \leq a \\ \tilde{\rho}(q_1, \dots, q_N) \tilde{\chi}_\rho \leq a \\ \text{VaR}_{\alpha^*}(I) \leq a \end{cases}$$

so in addition to partial derivatives, the Lagrange multipliers matter:

$$\begin{aligned} \sum_i \left[\underbrace{\frac{\partial s}{\partial q_i} \left[\mathbb{P}(I \geq a) + \tau - \sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} - v f_i(a) \right]}_{\text{Regulator driven allocation}} + \underbrace{\frac{\partial \tilde{\rho}}{\partial q_i} \times \left[\sum_k \frac{\frac{\partial v_k}{\partial a}}{v'_k} \right]}_{\text{Counterparty driven allocation}} + \underbrace{\frac{\partial \text{VaR}_{\alpha^*}(I^*)}{\partial q_i} \times [V f_i(a)]}_{\text{Shareholder driven allocation}} \right] \\ = a^* \times [\mathbb{P}(I \geq a) + \tau] \\ \Rightarrow a^* = \sum_j q_j^* \frac{\partial}{\partial q_j} ([1 - (\lambda_1 + \lambda_2)] s + \lambda_1 \tilde{\chi}_\rho \tilde{\rho} + \lambda_2 \text{VaR}_{\alpha^*})(I^*) \end{aligned}$$

The Euler Principle Revisited: General Case

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- ⇒ Euler principle works! Capital allocation can be implemented by differentiating **weighted average of external and internal risk measure** at current portfolio

Properties of $\tilde{\rho}$

Two influences:

1. **log-transform** – driven by limited liability

- In comparison to linear case (→Expected Shortfall) **less weight on extreme** loss states
- Counterparties evaluate changes in risk simply from the perspective of how the expected value of **recoveries** from the firm are affected
- Under complete markets, this reduces to Ibragimov et al. (2010) allocation

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- Under complete markets, this reduces to Ibragimov et al. (2010) allocation

2. **Change of measure** – driven by marginal utility in loss states:

- If **expected losses large** or **risk aversion high**, relatively **more weight on high loss states** → "more conservative"
- Evaluation for $X = I^*$:

$$\tilde{\rho}(I^*) = \exp \{ \mathbb{E} [\psi(I^*) \log(I^*) | I^* \geq a^*] \}$$

- $\psi(\cdot)$ similar as **risk spectrum** within **spectral risk measures** (Acerbi, 2002)
- Ultimately depends on $\psi(\cdot)$ how this "risk measure" compares and the ensuing allocation compares to other methods

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Homogeneous Exponential Losses

- ▶ Here, $l_i = q L_i$ and $l = q \sum L_i = q L$ and (obviously)

$$\frac{a_i}{a} = q \tilde{\phi}_i = \frac{1}{N} \mathbb{E} [\psi(L) | q L \geq a] = \frac{1}{N}$$

with

$$\psi(x) = \text{const} \times \sum_{k=0}^{\infty} \frac{(k+1)(\alpha(x-a))^k}{(N+k)!}$$

and

$$\tilde{\rho}(qL) = \exp \{ \mathbb{E} [\psi(L) \log \{ qL \} | qL \geq a] \}$$

- ▶ For Expected Shortfall, we have

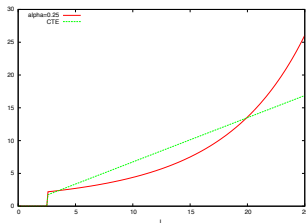
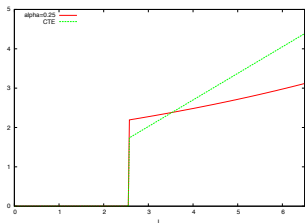
$$\frac{a_i}{a} = \frac{1}{N} \mathbb{E} [\text{const} \times L | qL \geq a] = \frac{1}{N}$$

- ▶ Analytical properties:

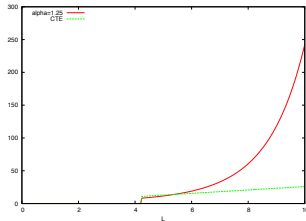
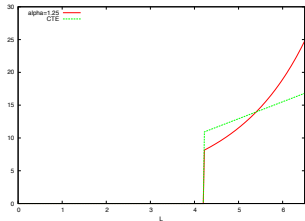
- ▶ ψ convex for $\alpha > 0$, particularly $\psi(x) = \text{const} \times \exp\{-\alpha(a-x)\}$ for $N = 1$
- ▶ ψ flat for $N \rightarrow \infty$ or $\alpha = 0$

Homogeneous Exp. Losses – two possible shapes for ψ :

Low risk aversion / small loss relative to wealth:



High risk aversion / large loss relative to wealth:



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- ▶ We identify the **optimal capital allocation** consistent with the **marginal cost** for a profit-maximizing firm with risk-averse counterparties, and the **supporting risk measure**
- ▶ This risk measure is generally **not convex** and **not coherent**, due to limited liability of the firm

Conclusion

- ▶ **Risk measure selection "thorny" issue** that can only be resolved by careful consideration of **institutional context**, particularly when the main purpose is the allocation of risk-based capital
- ▶ We identify the **optimal capital allocation** consistent with the **marginal cost** for a profit-maximizing firm with risk-averse counterparties, and the **supporting risk measure**
- ▶ This risk measure is generally **not convex** and **not coherent**, due to limited liability of the firm
- ▶ However, it includes a measure transform that puts the **focus on default states** and is related to **consumer's marginal utility in default states**. Hence, it may still **penalize high risk states more severely** than coherent risk measures
- ▶ Thus, the comparison to Expected Shortfall may result in **qualitative different outcomes**, depending on the size of the losses and risk aversion, among others

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Thank you!