Stochastic mortality under measure changes

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Talk based on joint work with David Blake (Cass), Lorenzo Pitotti (Imperial/Algorithmics), Ariel Sun (Imperial/RMS), Michel Denuit (UC Louvain), Pierre Devolder (UC Louvain)

Talanx, Hanover
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AGENDA

1. Motivation
2. Cox setting
3. Measure changes
4. Examples
5. Case study: Longevity swaps
6. Conclusion
MOTIVATION

Stochastic mortality models

- doubly stochastic/Cox setting ubiquitous
- pricing/valuation approaches vs. realistic risk analysis
- computational tractability vs. empirical evidence/performance
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Stochastic mortality models
- doubly stochastic/Cox setting ubiquitous
- pricing/valuation approaches vs. realistic risk analysis
- computational tractability vs. empirical evidence/performance

Same model for different purposes: is it asking too much?
- real world and risk-neutral world
- comparability: capital modelling and market-consistent valuation
- Cox setting has drawbacks, but can survive changes of measures
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- pricing/valuation approaches vs. realistic risk analysis
- computational tractability vs. empirical evidence/performance

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Mortality risk premia

- structure of risk premia often restrictive: broader structure valuable, often needed by setting
- reduced-form vs. structural/equilibrium approaches
  - bottom-up approaches to mortality risk premia
  - examples: asymmetric information, funding costs
COX SETTING

$m$ individuals aged $x_1, \ldots, x_m$ at time 0

- $\tau^i$ individual $i$’s random time of death
- $N_t = (N_t^1, \ldots, N_t^m)$, $N_t^i = 1_{\tau^i \leq t}$
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Information structure $F = G \lor H$
- $G = (G_t)_{t \geq 0}$ carries information about relevant risk factors (health status, reference populations, interest rates, etc.)
- $H = (H_t)_{t \geq 0} = \lor_{i=1}^{m} H^i_t$ carries information about death occurrences
  - each $H^i_t = (H^i_t)_{t \geq 0}$ augmented filtration generated by $N^i_t$
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Cox / doubly stochastic / conditionally Poisson assumption
- Conditional on $G_\infty$, each $N^i$ coincides with first jump of conditionally Poisson process with $G$-predictable intensity $(\mu^i_t)_{t \geq 0}$
- Conditional survival probabilities

\[ \mathbb{P}(\tau^i > T | F_t) = 1_{\tau^i > t} E \left[ e^{-\int_t^T \mu^i_s \, ds} \bigg| G_t \right] \]
Motivation Cox setting Measure changes Examples Case study: Longevity swaps Conclusion

PRO’S

- (Semi)explicitly survival probabilities in some settings (e.g., affine)

\[
E \left[ e^{- \int_0^T \mu_t^i \, dt} \right] = e^{A(0;T) + B(0;T) \cdot X_0}, \quad \mu_t^i = g^i(t, X_t)
\]

- Spread-based approach to market-consistent pricing and reserving

\[
E^\tilde{\mathbb{P}} \left[ \int_0^T e^{- \int_0^t r_s \, ds} D_t \, dN_t^i + e^{- \int_0^T r_s \, ds} S_T \, 1_{\tau^i > T} \right]
\]

\[
= E^\tilde{\mathbb{P}} \left[ \int_0^T e^{- \int_0^t (r_s + \mu_s^i) \, ds} D_t \mu_t^i \, dt + e^{- \int_0^T (r_t + \mu_t) \, dt} S_T \right]
\]

- Can easily simulate random death times

\[
\tau^i = \inf \left\{ t > 0 : \int_0^t \mu_s^i > \Theta \right\}, \quad \Theta \sim \text{Exp}(1)
\]
CON’S

Information and death/survival probabilities

- Cannot update conditional survival probability based on death occurrences

\[
P(\tau^i > T | G_t \lor H^1_t \lor \ldots \lor H^n_t) = P(\tau^i > T | G_t \lor H^i_t)
\]

- Example: Learning about the underlying force of mortality

Inconsistency across settings

- Cox may hold under \( \mathbb{P} \) but not under \( \tilde{\mathbb{P}} \sim \mathbb{P} \)
- Think of real-world/risk-neutral ESGs
- Example: risk-neutral Lee-Carter family

Inconsistency with approximate hedging methods

- natural incomplete market approaches inconsistent with Cox under \( \tilde{\mathbb{P}} \sim \mathbb{P} \)
- Example: Mean-Variance hedging with bespoke longevity swap
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EQUIVALENT MARTINGALE MEASURES

Girsanov-Meyer theorem

\[
\frac{d\tilde{P}}{dP} = \exp \left( - \int_0^T \frac{1}{2} \|\eta_s\|^2 ds - \int_0^T \eta_s \cdot dW_s \right) \prod_{i=1}^m \left( 1 + \phi^{i}_{\tau^i} 1_{\tau^i \leq T} \right) \exp \left( \int_{0}^{\min(\tau^i, T)} \phi^{i}_{\tau^i} \mu^{i}_{\tau^i} ds \right)
\]

- \( \tilde{W}_t = W_t + \int_0^t \eta_s ds \) B.m. under \( \tilde{P} \)
- each \( \tau^i \) has intensity \( 1_{\tau^i > t}(1 + \phi^{i}_t)\mu^{i}_t \) under \( \tilde{P} \)

Cox setting survives when switching to \( \tilde{P} \sim P \) if \( (\eta, \phi^1, \ldots, \phi^m) \) \( \mathbb{G} \)-predictable
MORTALITY RISK PREMIA

**Systematic** mortality risk
- affects the conditional death probability of each individual in the portfolio
- channelled by $(\eta_t)_{t \geq 0}$

**Unsystematic** mortality risk
- depends on portfolio size, $m - \sum_{i=1}^{m} N_t^i$
- jointly captured by $\phi_t^1(1 - N_t^1), \ldots, \phi_t^m(1 - N_t^m)$

**Individual death timing** risk
- captured by each $\phi_t^i(1 - N_t^i)$
- relevant whenever insurance demand (e.g., pricing) or policyholders’ preferences (American-type guarantees, dynamic adverse selection) matter

The last two involve a change in intensity process, $\mu_t^i \sim \mu_t^i(1 + \phi_t^i)$, the first one does not.
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EXAMPLE: LEARNING

Death times $\tau^1, \ldots, \tau^m$ have common intensity $\mu$

- assume that $Y := \log \mu$ evolves according to

\[
dY_t = (a(t) + b(t)Y_t + c(t)\psi)dt + \sigma(t, Y_t)dW_t
\]

Insurer observes $Y$

- recovers $\sigma$ from quadratic variation of $Y$, and draws inferences about drift in Bayesian fashion, backing out from observations of $Y$ the true value of $\psi$
- think of insurer endowed with $(F^Y, \tilde{P})$, with $\tilde{P}$ subjective probability measure reflecting Bayesian updating based on prior beliefs on $\psi$

\[
\begin{align*}
\eta_t &= \frac{c(t)(\psi - \Psi_t)}{\sigma(t, Y_t)} \in G_t, \\
\phi^i &= 0
\end{align*}
\]
EXAMPLE: LEARNING

Death times $\tau^1, \ldots, \tau^m$ have common intensity $\mu$
  - assume that $Y := \log \mu$ evolves according to

  $$dY_t = (a(t) + b(t)Y_t + c(t)\psi)dt + \sigma(t, Y_t)dW_t$$

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  $$\eta_t = \frac{c(t)(\psi - \Psi_t)}{\sigma(t, Y_t)} \in \mathcal{G}_t, \quad \phi^i = 0$$

Suppose the insurer uses $(Y, N)$
  - $\eta, \phi^1, \ldots, \phi^m$ depend on $N$: the Cox setting does not survive...
EXAMPLE: MEAN-VARIANCE HEDGING

Liability

- portfolio of indexed survival benefits (e.g., $\sum_{i=1}^{m} 1_{\tau^i > T} f(S_T)$)

Tradeables

- index $(S_t)_{t \geq 0}$
- bespoke longevity swap, it spans $(N_t)_{t \geq 0}$

Approximate hedging method

- minimize mean-square error of A/L mismatch at $T > 0$
- $\widetilde{P}$ entails $\mathbb{F}$-predictable $(\eta, \phi^1, \ldots, \phi^m)$
  - Cox setting does not survive change of measure
- $\widetilde{P}$ entails $\phi^i \neq 0$
  - portfolio size attracts a risk premium
EXAMPLE: ADVERSE SELECTION IN THE BUYOUT MARKET

Source: Biffis/Blake (2011)
EXAMPLE: SECURITIZATION WITH ASYMMETRIC INFORMATION

Source: Biffis/Blake (2010a)
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### SOME TRANSACTIONS

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<th>Date</th>
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<th>Type</th>
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<td>JPM ILS funds</td>
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<td>indemnity</td>
<td>DB Paternoster</td>
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<td>ILS funds</td>
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<td>10</td>
<td>indexed</td>
<td>JPM</td>
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LONGEVITY SWAPS

Main issues
- Dodd-Frank, EMIR bespoke solutions
- counterparty risk is bilateral
- longevity risk premium meaningless if MTM/collateral flows ignored

Reference model
- IRS market: bilaterally collateralized, cash collateral in over 90% of the cases
- collateral thresholds based on mark-to-model, mortality experience, credit ratings, CDS spreads, etc.

Questions
- collateral vs. capital
- pricing/valuation with bilateral default risk and collateral
- longevity swaps vs. IRSSs
BESPOKE SOLUTIONS

Stylized example: single payment at time $T$
- notional $n$, fixed payment $\bar{p} \in (0, 1)$
- variable payment $S_T$ (realized survival rate)
BESPOKE SOLUTIONS

Stylized example: single payment at time $T$

- notional $n$, fixed payment $\bar{p} \in (0, 1)$
- variable payment $S_T$ (realized survival rate)

\[ V_0 = nE^Q \left[ \exp \left( - \int_0^T r_t dt \right) (S_T - \bar{p}) \right] \]
BESPOKE SOLUTIONS

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![Diagram: Hedger (H) to Hedge Supplier (HS) with formulas $n \times \bar{p}$ and $n \times S_T$]

Longevity swap rate

$$\bar{p} = E^Q[S_T] + \frac{\text{Cov}^Q\left(\exp\left(-\int_0^T r_t dt\right), S_T\right)}{E^Q\left[\exp\left(-\int_0^T r_t dt\right)\right]}$$
BESPOKE SOLUTIONS

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Longevity swap rate ($r, S$ uncorrelated)

$$\bar{p} = E^Q [S_T] + 0$$
BESPOKE SOLUTIONS

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Longevity swap rate ($r, S$ uncorrelated)

\[
\bar{p} = E^Q [S_T] + 0
\]

Useful baseline case $\bar{p} = E^P [S_T]$ (best estimate).
BACKTESTING

UK-based hedger

- 10,000 individuals (England & Wales) aged 65 in 1980
- indemnity-based solution over 1980 – 2005
- interest rate risk hedged away

Realized cashflows

- population evolves as in Human Mortality Database (HMD)
- cashflow hedge in operation: \((realized\ rate) - (swap\ rate)\)

Marking to market/model (MTM)

- swap curves given by Lee-Carter forecasts based on most recent HMD data available
CASHFLOWS AND MTM
HEDGE SUPPLIER’S CREDIT DETERIORATION
HEDGE SUPPLIER’S CREDIT DETERIORATION
VALUATION

Hedger’s viewpoint, cash collateral

- default intensities \((\lambda^h_t)_{t \geq 0}, (\lambda^{hs}_t)_{t \geq 0}\)
- collateral fraction, \((c_t)_{t \geq 0}\), of market value, \((V_t)_{t \geq 0}\)
- \(c_t V_t\) amount held (if pos.) or posted (if neg.)
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- \(c_t V_t\) amount \textit{held} (if pos.) or \textit{posted} (if neg.)
- collateral cost, \((\delta_t)_{t \geq 0}\)
  - \textbf{funding} cost
  - \textbf{opportunity} cost of buying/selling additional longevity protection
- asymmetry in \(c, \delta\) possible
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  - * funding cost
  - ** opportunity cost of buying/selling additional longevity protection
- asymmetry in \(c, \delta\) possible
- swap market value (Biffis/al., 2011; Duffie/Huang, 1996; Brigo/al., 2008-)

\[
V_0 = \mathbb{E}^Q \left[ \exp \left( - \int_0^T (r_t + \Gamma_t) \, dt \right) (S_T - \bar{p}^c) \right]
\]

\[
\Gamma_t := \begin{cases} 
(1 - c^h_t)\lambda^h_t - \delta^h_t c^h_t & \text{if } V_t < 0 \\
(1 - c^{hs}_t)\lambda^{hs}_t - \delta^{hs}_t c^{hs}_t & \text{if } V_t \geq 0 
\end{cases}
\]
FULLY FLEDGED CALIBRATION

Building blocks

- two-factor short rate model
- TED spread for $\lambda^{hs}$
- $\lambda^h = \lambda^{hs} + \Delta$, $\Delta > 0$
- mortality: Lee-Carter mortality model
- implied IRS collateral costs (Johannes/Sunadersan 2007)

Two approaches to collateral net costs $\delta^h, \delta^{hs}$

1. funding costs associated with collateral flows
2. simulate Solvency II capital charges (1-year 99.5% VaR) accruing from representative longevity-linked liability, then use $\text{Libor} + 6\%$ or $12\%$ for cost of capital charges
LONGEVITY SWAP MARGINS

Swap margins, $\frac{\bar{P}^c}{E^P[S_T]} - 1$, against Lee-Carter mortality improvements quantiles.
LONGEVITY SWAP MARGINS

Swap margins, \( \frac{\bar{D}^c}{E^P[ST]} - 1 \), against Lee-Carter mortality improvements quantiles.
LONGEVITY SWAP MARGINS

Swap margins, $\frac{P^c}{E^P[S_T]} - 1$, against Lee-Carter mortality improvements quantiles.
LONGEVITY SWAP MARGINS

Swap margins, \( \frac{\bar{P}^c}{E^P[S_T]} - 1 \), against Lee-Carter mortality improvements quantiles.
LONGEVITY SWAP SPREADS

Swap spreads (basis points), $\bar{p}_T^c - E^P[S_T]$

<table>
<thead>
<tr>
<th>$\lambda^h = \lambda^{h,hs} + \Delta$</th>
<th>Maturity</th>
<th>$c^h = 0$</th>
<th>$c^{hs} = 0$</th>
<th>$c^h = 1$</th>
<th>$c^{hs} = 0$</th>
<th>$c^h = 1$</th>
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<td>(bps)</td>
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## COMPARISON WITH THE IRS MARKET

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<th>Maturity payment (yrs)</th>
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$\Delta = 0$

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4 Examples

5 Case study: Longevity swaps

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CONCLUSION

Stochastic mortality models
- make sure (implicit) assumptions meet your needs
- consistency across applications is important and can be achieved

Mortality risk premia
- “standard” assumptions should not be taken at face value
- you can get a lot of mileage from restrictive models
- endogenizing risk premia through real world frictions (e.g., signalling, funding costs) is likely to require much richer structure than usually assumed
CONCLUSION

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- make sure (implicit) assumptions meet your needs
- consistency across applications is important and can be achieved

Mortality risk premia

- “standard” assumptions should not be taken at face value
- you can get a lot of mileage from restrictive models
- endogenizing risk premia through real world frictions (e.g., signalling, funding costs) is likely to require much richer structure than usually assumed

More details and references available in (see www.ssrn.com)

- Biffis/Denuit/Devolder (2010), Stochastic mortality under measure changes
- Biffis/Blake (2010a), Securitizing and tranching longevity exposures
- Biffis/Blake/Pitotti/Sun (2011), The cost of counterparty risk and collateralization in longevity swaps
- Biffis/Blake (2011), Informed intermediation of longevity exposures
THANK YOU FOR YOUR ATTENTION