## 5.2節，5.7節，5.8節　死力の定義とその確率的なモデル化

本節では，まず初めに死力や生存率等，今後必要となる生保数理的な量について定義を行い，その後，死力のモデル化について記載する．

人間が死亡する時刻の確率密度関数を考える．定義より，を寿命の最大値であるとすると，以下の式が成立する．

|  |  |
| --- | --- |
|  | (1) |

この確率密度関数を用いると，死亡率，生存率，死力が以下の式で定義できる．

|  |  |
| --- | --- |
|  | (2) |

ここで死力とは，歳に到達した人が次の瞬間に死亡する確率を表す[[1]](#footnote-1)．

死力の確率的なモデルではある値に均衡するのが望ましい．ただし，均衡値については時間に依存する量を仮定する．これは，一定値であるとすると生存率が現在の年齢に依存しない算式となるためである．実際，死力が時刻からの間一定値となった場合，生存率は以下のように計算され，年齢に依存しないことがわかる．

|  |  |
| --- | --- |
|  | (3) |

時間に依存する均衡値を持つ死力の確率的モデルとして以下のモデルを使用する．

|  |  |
| --- | --- |
|  | (4) |

伊藤の公式を用いた後に，期待値をとることで以下の式を得る．

|  |  |
| --- | --- |
|  | (5) |

ここで以下の２点を仮定する．

1. の初期値との初期値が等しい：
2. 死力の期待値はGompertz-Makehamモデルと一致する：
3. と(5)式により，死力の期待値について以下の式が成立する．

|  |  |
| --- | --- |
|  | (6) |

さらに，②の仮定を踏まえれば，は以下のようになる．

|  |  |
| --- | --- |
|  | (7) |

CIR過程の性質を利用するためにを以下の式で仮定する．

|  |  |
| --- | --- |
|  | (8) |

最終的に死力の確率過程として以下の式をが得られる．

|  |  |
| --- | --- |
|  | (9) |

## 6.2節，6.3節　生保数理的な金融商品

生保数理的な量（死力や生存率など）を原資産として持つデリバティブはクーポンや満期でのペイオフが人口動態的な量を用いて書かれる債券であると考えることができる．したがって，このようなデリバティブの価格は一般的に以下の算式で与えられる．

|  |  |
| --- | --- |
|  | (10) |

長寿債券とはクーポンが時刻から時刻までの生存率で表される債券である．したがって価格は以下の式で表される．

|  |  |
| --- | --- |
|  | (11) |

(11)式より，長寿債券は満期までの期間で代表的な被保険者が生存している期間まで単位通貨のクーポンが得られる債券であると解釈できる．

さらに，死力と金利の確率過程が独立であると仮定すると，以下のように変形できる．

|  |  |
| --- | --- |
|  | (12) |

ここではリスク中立測度の下での生存率である．

この式より，長寿債券は，複数のゼロクーポン長寿債券の集まりと見なすことができる．

|  |  |
| --- | --- |
|  | (13) |

## 7.3節，7.4節　責任準備金

年金ファンドの正味のアウトフローの事を数理的責任準備金という．すでに支払われた保険料を考慮に入れるといくつかの数理的責任準備金が存在するが，以降では以下のPMR（Prospective Mathematical Reserve）を用いる．

|  |  |
| --- | --- |
|  | (14) |

PMRは年金ファンドが年金の支払いのためにどの程度資産を保有すべきかという事を知るために使われる．したがって，PMRはある決められた水準の年金を支払うDBでよく使用される．

次にいくつかの仮定の下で，PMRを実際に計算し，その性質を確認する．まず初めに，金利，死力，保険料，年金が一定である場合を考える．この場合，PMRは以下のような簡単な形になる．

|  |  |
| --- | --- |
|  | (15) |

右辺の積分を実行したのち，feasible conditionから算出された保険料と年金の関係式[[2]](#footnote-2)を使用すると，最終的に以下の算式になる．

|  |  |
| --- | --- |
|  | (16) |

図 **1**は，，，とした場合のPMRである．65歳以降でPMRは一定となっているが，これは死力が一定であることから，年齢から年齢()までの間に死亡する確率はに依存せず，年金ファンドは年金支払いを保証するために一定の資産を保持しなければならないためである．

![グラフ, 折れ線グラフ

自動的に生成された説明](data:image/jpeg;base64,/9j/4AAQSkZJRgABAQEAYABgAAD/4RDaRXhpZgAATU0AKgAAAAgABAE7AAIAAAAFAAAISodpAAQAAAABAAAIUJydAAEAAAAKAAAQyOocAAcAAAgMAAAAPgAAAAAc6gAAAAgAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAEFpIFkAAAAFkAMAAgAAABQAABCekAQAAgAAABQAABCykpEAAgAAAAM2MwAAkpIAAgAAAAM2MwAA6hwABwAACAwAAAiSAAAAABzqAAAACAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA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図 1 各量を一定とした場合のPMR

次に死力としてGompertz関数を用いた場合を考える．上述のパターンと同様に計算を実行すると，以下の式が導ける．

|  |  |
| --- | --- |
|  | (17) |

米国のデータを使用してGompertzパラメータを推計し，PMRを算出した結果が以下の図 2である．

![グラフ, 折れ線グラフ

自動的に生成された説明](data:image/jpeg;base64,/9j/4AAQSkZJRgABAQEAYABgAAD/4RDaRXhpZgAATU0AKgAAAAgABAE7AAIAAAAFAAAISodpAAQAAAABAAAIUJydAAEAAAAKAAAQyOocAAcAAAgMAAAAPgAAAAAc6gAAAAgAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAEFpIFkAAAAFkAMAAgAAABQAABCekAQAAgAAABQAABCykpEAAgAAAAM0NQAAkpIAAgAAAAM0NQAA6hwABwAACAwAAAiSAAAAABzqAAAACAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA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cMWu3Wqq0hnuraG2dSRtCxNKykDGc5mbPPYdOcgGV/whGlf8/eu/+FDf/wDx6j/hCNK/5+9d/wDChv8A/wCPV0NFAHPf8IRpX/P3rv8A4UN//wDHqP8AhCNK/wCfvXf/AAob/wD+PV0NFAHPf8IRpX/P3rv/AIUN/wD/AB6j/hCNK/5+9d/8KG//APj1dDRQBz3/AAhGlf8AP3rv/hQ3/wD8eo/4QjSv+fvXf/Chv/8A49XQ0UAc9/whGlf8/eu/+FDf/wDx6j/hCNK/5+9d/wDChv8A/wCPV0NFAHPf8IRpX/P3rv8A4UN//wDHqP8AhCNK/wCfvXf/AAob/wD+PV0NFAHPf8IRpX/P3rv/AIUN/wD/AB6j/hCNK/5+9d/8KG//APj1dDRQBz3/AAhGlf8AP3rv/hQ3/wD8eo/4QjSv+fvXf/Chv/8A49XQ0UAc9/whGlf8/eu/+FDf/wDx6j/hCNK/5+9d/wDChv8A/wCPV0NFAHPf8IRpX/P3rv8A4UN//wDHqzZNDgtfF1no0N7q/wBh1DTbqedX1i6dy8UtsEKyNIXTAlcEKQGzznAx2dU5dLhl1211VmkE9rbTWyKCNpWVomYkYznMK457nrxgAyv+EI0r/n713/wob/8A+PUf8IRpX/P3rv8A4UN//wDHq6GigDnv+EI0r/n713/wob//AOPUf8IRpX/P3rv/AIUN/wD/AB6uhooA57/hCNK/5+9d/wDChv8A/wCPUf8ACEaV/wA/eu/+FDf/APx6uhooA57/AIQjSv8An713/wAKG/8A/j1H/CEaV/z967/4UN//APHq6GigDnv+EI0r/n713/wob/8A+PUf8IRpX/P3rv8A4UN//wDHq6GigDnv+EI0r/n713/wob//AOPUf8IRpX/P3rv/AIUN/wD/AB6uhooA57/hCNK/5+9d/wDChv8A/wCPUf8ACEaV/wA/eu/+FDf/APx6uhooA57/AIQjSv8An713/wAKG/8A/j1H/CEaV/z967/4UN//APHq6GigDnv+EI0r/n713/wob/8A+PVJa+DdJtNStb5W1Kee0dpIPterXVwqMUZCwSSRlztdhnHc1u0UAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQBDeXcFhYz3l5IsVvBG0ksjdFUDJJ/CsLRfGtprGow2b6dqOmyXUBuLM30SKLqMYyybWbGAynDbTg9OtP8e6fc6r8PddsbBDJcz2MqRovV22nAH16VzMGtad4r8ZeED4fuY7oabDPcXvknP2YNF5Yjkx91ix+6eflPpTjq/wCvMHov68j0aiiikAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFAHP6x4uh0vVhplrpmo6tfCD7RLDYRoTDGSQGYu6jkg4AJJweKhl8d6YdM0y6063vNTl1UMbS0tY185wv3yQ7KF29DkjnjrWH478f2Oja3H4cttUsdK1C6g8y41G8YBbSEnAKj+OQ87V6DqfQ0reXQPDet+EtVsr+EeGk026so9RklHlCVnjYM7ngFij8nGTRHVa/1v/wED0f9eX/D+h32ha5a+INMF7ZCVAHaKSGZdskMinDIw7EEe49Ca0a4/wCHQM9nrepxhvsmp6xPc2pIIDxYVA4z2YoSD3BzXYU30+X5C7/MKKKKQwooooAKKKKACiiigAooooAKKKKACiiigAooooAq6lqVrpGmXGoahKsNtbRmSR27AViL460x/COneIIoLuSLUyi2dosameZ2zhAu7GeCeWwACSaoeNrLxFfatYHTtKs9S0q0UzyQT3xty84+4T+7bKr94Du2D2rjPD9xdW3w+8Aaxq9tHaafpd7mWVZvMVYWhkRZn+UbAGcA9cdc0R137ob0+5/keo6D4it9eS5WO3ubO6s5fKubS7VVlhYgMM7SVIIIIIJFa1cV4Onh1fxr4o1zTZVn024NtbwXEZzHO0aNvZG6MAXC5HGQfSu1pskKKKKQwooooAKKKKACiiigAooooAKKKKACiiigAooooAzNe1618PWCXN2k0zyyrBBb26b5Z5G6IoyBngnkgAAkkCsg/ECwjsp3udO1K3voblLT+zJIk+0SSuMoq4co2Rk53YAByRisv4pWnmf8I5e3F1cWWnWep7r27t5CjQRtE6biw5UZYAt23ZyOtcnHeJbeI7bULPU5tR8H6PrETJfz3DXCQmS3kSTErElo1dk+YkgFjzxTjrv/AFt/n/XUen3f5/5Hqmg+IrfXkuVjt7mzurOXyrm0u1VZYWIDDO0lSCCCCCRWtXFeDp4dX8a+KNc02VZ9NuDbW8FxGcxztGjb2RujAFwuRxkH0rtaGIKKKKQwooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigApFRUzsULuOTgYyfWlooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKR0WRSsihlPUEZBpaKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACggMCGGQeCD3oooARVCKFQBVAwABgCloooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAIBBBGQeoNNEaLHsVFCYxtA4x9KdRQAiqEUKgCqBgADAFLRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFcP45uDda7pWiQLqNzNPFNObK0vvsSSIu0bpJgQ2AWHyrnOckcUhncUV4l4U1W71+/sdD8QavdwaWk+oKjQ6nJmd4pECRG5G13CqzHOQWwCelDa5rJ8MQ2em6nc6lBdeKLixN1LqLQs8CglIxcAMUBKgZAyegxnNPe1uuv4pfqTt8nb8G/0PbaK4b4dyarFfa5pupPGsFpLF5Nr/ab38lqWUlkaV1DEdCAckZPtXc02AUUUUhhRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFZ2r+H9H1+OOPXNLs9RSJt0YuoFk2H2yOK0aKAOT8Q+Clv7eCLRYtHtoEdnmsb7S0uLWdiAA7ICpDjAwwPsR0xZ0HwZY6V4Xl0bUUt9TjuppJ7oSWyrFI7tuOI+QqjgAc4AHNdHRQBT0vSNO0SyFno9jb2NspJEVtEI1yepwO/vVyiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigD//2Q==)

図 2　PMR(Gompertz死力)

40歳まで保険料の払い込みがあるため，40歳で積立金が最大になる．死力が一定であった場合とは異なり，死亡する確率が年齢と共に大きくなるため，PMRは40歳以降一定ではなく，低下する．

## 7.5節　ファンド富の確率的な変動

市場に個のリスク性資産と安全資産があり，以下の確率微分方程式を満たすとする．

|  |  |
| --- | --- |
| ：対角成分がである対角行列．  ：次元ベクトル  ：行列  ：次元のブラウン運動 | (18) |

この時ファンドの富は以下のように表される．

|  |  |
| --- | --- |
| ：リスク性資産のウェイト（次元ベクトル）  ：安全資産のウェイト | (19) |

の確率的な変動は以下のように表される．

|  |  |
| --- | --- |
|  | (20) |

ここで，ポートフォリオに対する富の引き出しや投入をと表すと，self-financing条件より，

|  |  |
| --- | --- |
|  | (21) |

となるので，富の変動は以下の確率微分方程式で表される．

|  |  |
| --- | --- |
|  | (22) |

## 7.6節　ファンドアロケーションの決定

年金ファンドのアロケーションを決める際に使う目的関数は様々であるが一般的なものとして，加入者の死亡時点におけるファンドの富に対する効用関数の期待値を目的関数とし，それを最大化することでアロケーションを決める方法がある．具体的には以下の値を目的関数にする．

|  |  |
| --- | --- |
| ：投資ウェイト  ：加入者が加入した時点  ：加入者が死亡した時点  ：年金ファンドの効用関数  . ：加入者が死亡した時点でのファンドの富  ：主観的な割引ファクター[[3]](#footnote-3) | (23) |

さらに，効用関数としては以下のHARA型を仮定する．

|  |  |
| --- | --- |
| ：パラメータ（） | (24) |

はファンドの富のパーセントで最低限到達すべき富の水準である．

## 7.8節　動的最適化（マルチンゲールアプローチ）

最適なポートフォリオを算出するために，２段階に分けて計算する．

1. 最適なポートフォリオの価値を計算する．
2. そのポートフォリオを複製するようなウェイトを決定する．

まずは①の計算をするために，以下の最適化問題を解く．なお，初期時点の富の制約は代表的契約者が死亡した時点において，その時点の富のパーセントを保持することができるという制約条件を表す．

|  |  |
| --- | --- |
|  | (25) |

ラグランジアンの未定乗数法を用いて最適な富を求めると以下の算式になる．

|  |  |
| --- | --- |
|  | (26) |

効用関数の形から示唆される通り，最適な富は必ずよりも大きい事がわかる．

次に，最適な富を複製するようなウェイトを計算する．時刻において，現在の富と将来の保険料，年金及び富のパーセントを保持することを踏まえた以下の式が成立する．

|  |  |
| --- | --- |
|  | (27) |

この式の右辺のに最適な富(26)を代入すると，

|  |  |
| --- | --- |
| ここで， | (28) |

伊藤の公式を用いると，富の微小変動は以下のように書けることがわかる．

|  |  |
| --- | --- |
|  | (29) |

一方で，(22)式より拡散項を比較すると以下の式が成立する．

|  |  |
| --- | --- |
|  | (30) |

市場が完備であるとすると，ポートフォリオのウェイトは以下のようになる．

|  |  |
| --- | --- |
|  | (31) |

第一項は投機的ポートフォリオとよばれ，マートンのポートフォリオと一致する．一方で，第二項はヘッジングポートフォリオと呼ばれ，状態変数の確率的な変化に対するヘッジの必要性のために生じるものである．

## 8.2節　状態変数

状態変数が従う確率微分方程式を以下の形で仮定する[[4]](#footnote-4)．

|  |  |
| --- | --- |
|  | (32) |

なお，保険契約者が手に入れる年金は一定であるとし，この一定値はPMRが0になる点で決められる．また，(32)で導入したウィーナー仮定はすべて独立であるとする．

リスク中立測度の下でも統計的な性質が変わらないようにするためには，リスクの市場価格を以下のように設定する必要がある．

|  |  |
| --- | --- |
|  | (33) |

については一定値にする必要がある．この条件の下，リスク中立測度下での確率微分方程式は以下のようになる．

|  |  |
| --- | --- |
|  | (34) |

最後に，簡単のため，主観的割引率は一定であるとする．

## 8.4節　金融市場

金融市場には３つのリスクが存在するため，市場の完全性を満たすには３つの（完全相関しない）資産が存在しなければならない．本分析では，リスク資産として株式，割引債，長寿債券の３つを想定する．

* 株式

パラメータを定数として，株式の価格が以下の確率微分布袋式に従うとする．

|  |  |
| --- | --- |
|  | (35) |

* 割引債

一定の満期を持つ割引債を考える．この債券の価格は以下の通りである．

|  |  |
| --- | --- |
|  | (36) |

また，確率微分方程式の形で書けば，

|  |  |
| --- | --- |
|  | (37) |

* 長寿債券

この債券では，満期において代表的契約者が生存していたら１のキャッシュフローがあるという債権である．なお，簡単のため，債券と同じ満期であるとする．この債券の価格は以下の式で与えられる．

|  |  |
| --- | --- |
|  | (38) |

また，確率微分方程式の形で書けば

|  |  |
| --- | --- |
|  | (39) |

となる[[5]](#footnote-5)

以上の式を行列形式で記載すると以下のようになる．

|  |  |
| --- | --- |
|  | (40) |

## 8.5節　使用データ

本節ではこの後のカリブレーションおよびシミュレーションに向けて使用するデータを選定する．

データの期間としてはリーマンショックによる影響を避けつつ，できるだけ長い期間を使用することに注意し，1970年1月1日から2007年1月1日とした．

* 無リスク金利は３か月国債のリターンを使用してカリブレーションする．（FREDにより作成．シリーズコード「DTB3」）
* 割引債の満期は10年とし，10年国債のリターンから計算する（FREDにより作成．シリーズコード「DGS10」）

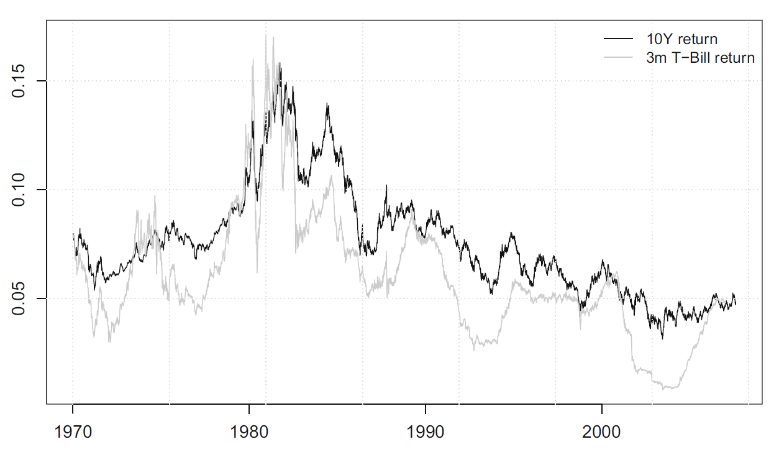


図 3 米国３か月国債と10年国債のリターン推移

* リスク資産はS&P500であるとする．

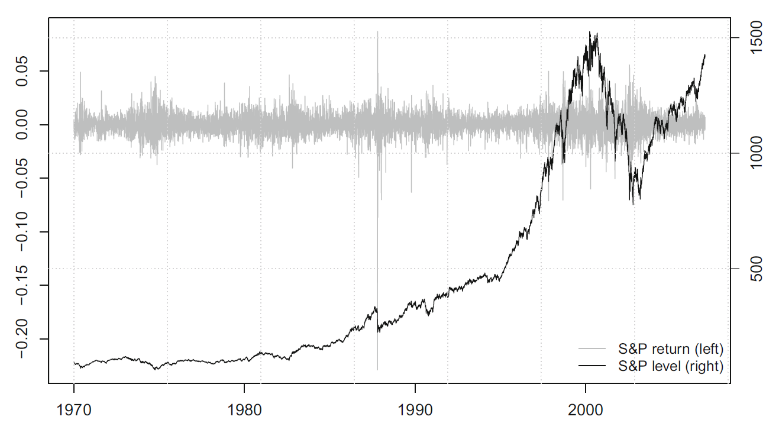


図 4　S&P500の推移(右軸)，リターン(左軸)

* 保険料は労働収入に比例すると仮定する[[6]](#footnote-6)．

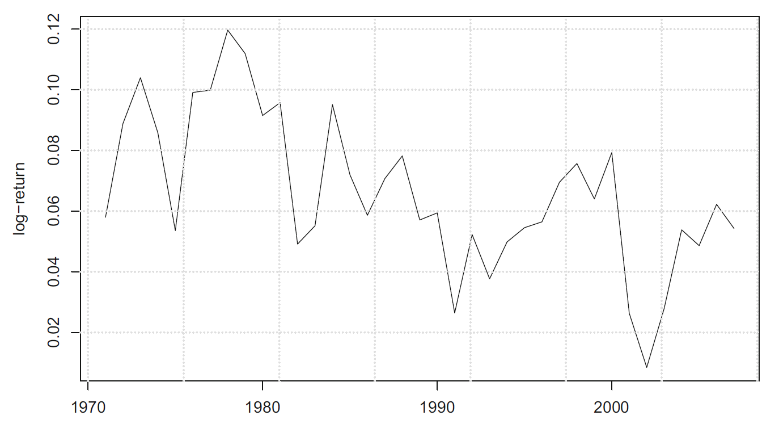


図 5　労働収入の対数リターンの推移

* 米国の死力のデータとしてはHMD（Human Mortality Database）を使用する．

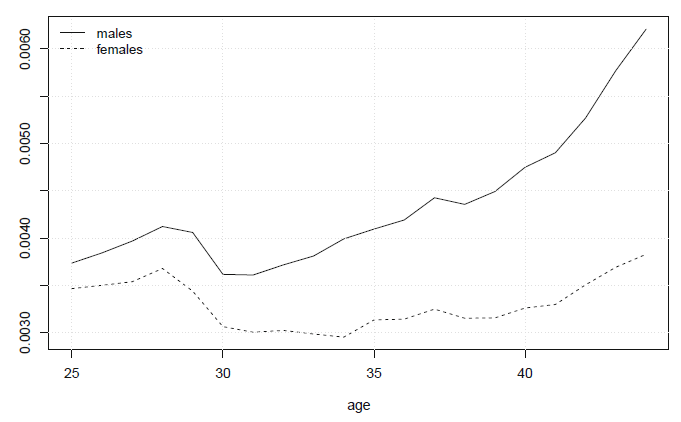
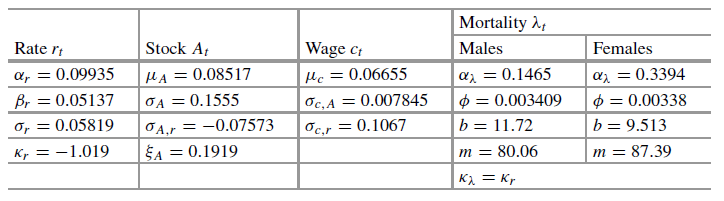


図 6　死力のデータ（米国，25歳，1993年）

## 5.8節,8.6節,8.7節,8.8節　カリブレーション

上述のモデルに対してカリブレーションを行い，パラメータ推計をする．カリブレーションの方法としてはモデルから算出されるモーメント（平均，分散）及び相関係数がヒストリカルデータと一致させるように設定（モーメント法）する．結果としては以下のとおりである．

表 1 パラメータ推計結果



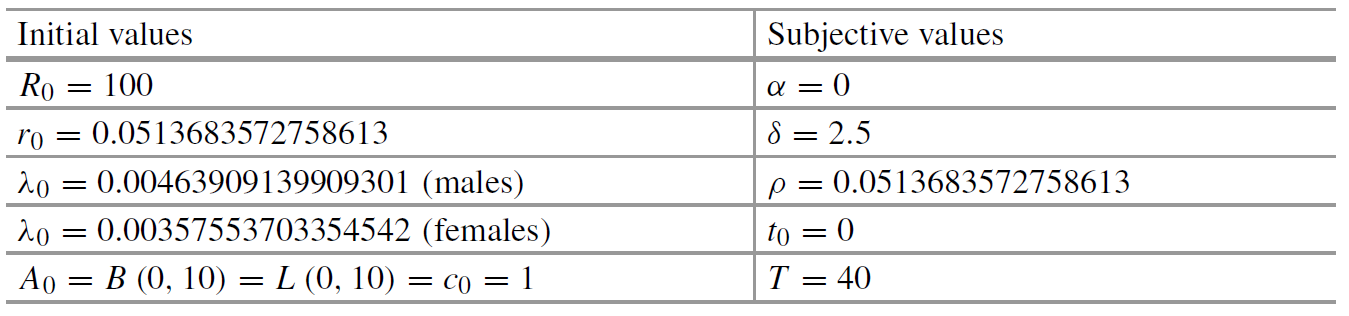
ただし，については保険統計的なリスクに対する市場価格と金利のリスクに対する市場価格が同じ値であると仮定している[[7]](#footnote-7)．

## 8.12節　シミュレーション

最適なポートフォリオのシミュレーションをするにあたり，予め初期値や年金基金の効用関数のパラメータを決めておく必要がある．なお，効用関数としてはHARA型を仮定する．

初期値および効用関数のパラメータは以下のとおりとする．

表 2 初期値及びパラメータ

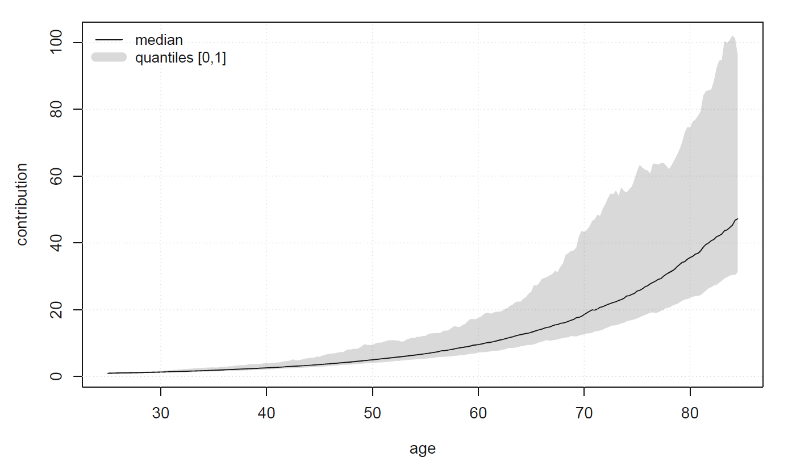


また，以降のシミュレーションにおいては100個のパスを生成する．

まず，リスクフリーレートおよび死力・保険料のシミュレーション結果は図 **7**の通りである．特徴としては，以下の点があげられる．

* 金利のシナリオについては平均回帰の水準付近に平均値があり，平均回帰性が確認できる．
* 死力のシナリオでは平均的に女性の方が長生きすることがわかる．また，シナリオの分散も女性の方が小さいことがわかる．

グラフ, 折れ線グラフ, ヒストグラム

自動的に生成された説明

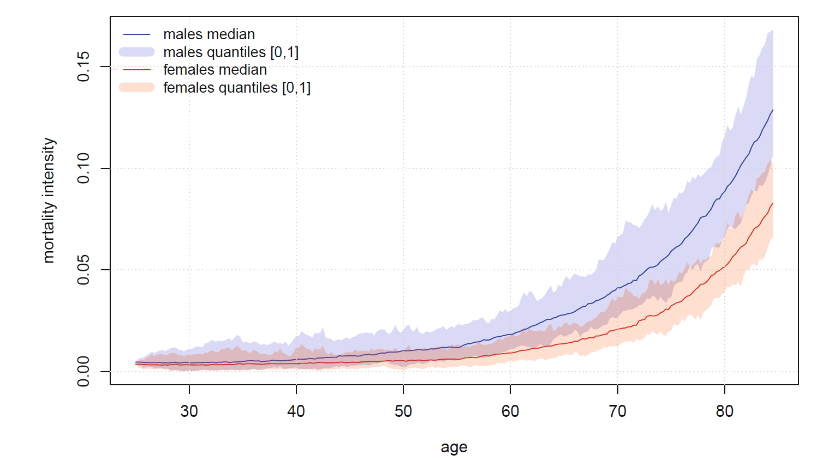


図 7　金利（上段左），保険料（上段右），死力（下段）のシミュレーション結果

責任準備金（PMR）のシナリオは図 8のとおりである．65歳以降に年金の支払いが始まるため，65歳から責任準備金が減少している．男性については，死力のシナリオが示すように死亡する確率が女性と比較して高く，そのため積立金を女性よりも多くする必要がある．

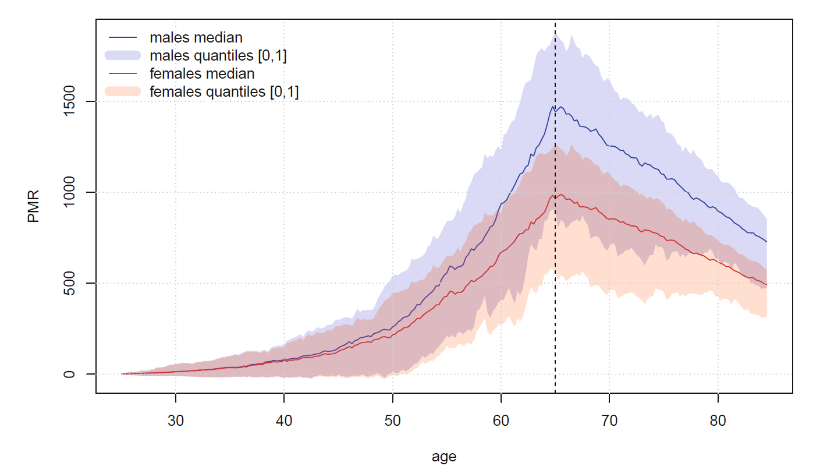


図 8　責任準備金のシミュレーション結果

最適投資をした場合のファンドの富はのとおりである．退職前の富のリターンは横ばいだが，退職後には上昇していることがわかる．これは，ヘッジ戦略に起因するものである．退職前は退職後に比べてヘッジの重要性が高いため，ポートフォリオのリターンを放棄してヘッジする．したがって，退職後との比較ではリターンが低くなる．

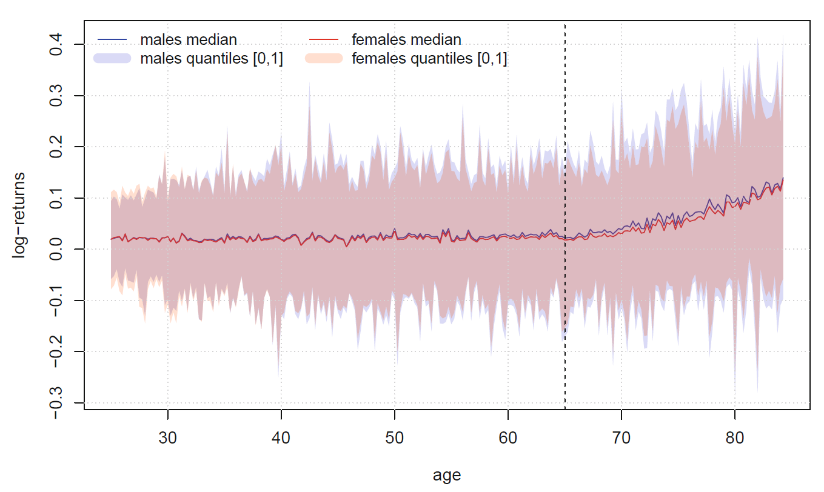


図 9　最適な富の対数リターン

ポートフォリオのアロケーションについて，ファンドの富に占めるリスク資産（株式，10年国債，長寿債券）の推移は図 10の通りである．退職を境にしてリスク資産の割合が減少から増加に転じ，その後ある種の均衡値に達したのちに減少するグラフになっている．直感的には契約者の年齢が上がるにつれてリスクを低下させる方がよいとされるが，退職時点まではこの主張と整合的である．

ファンドの富には最低限下回ってはいけない水準が存在する．例えば責任準備金やファンドの運営にかかる費用等である．このような金額をファンドの富から差し引いたものを修正富と呼ぶ．修正富に占めるリスク資産の割合は図 10の右図である．通常の富に占める割合の推移とは退職後の振る舞いが異なり，徐々に減少していることがわかる．

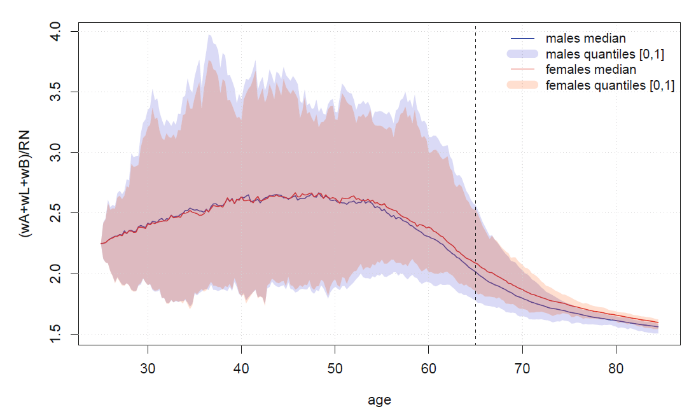
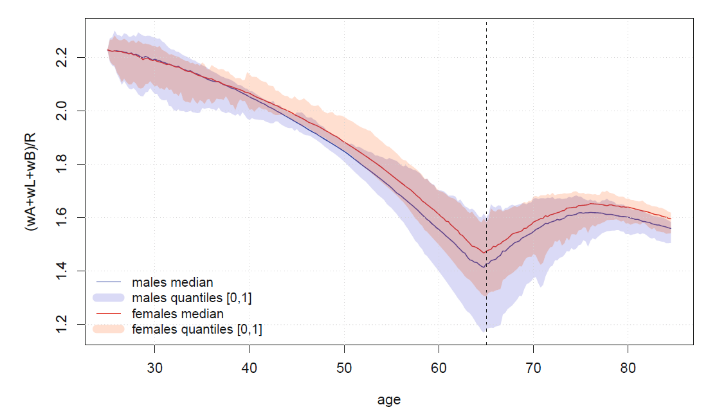
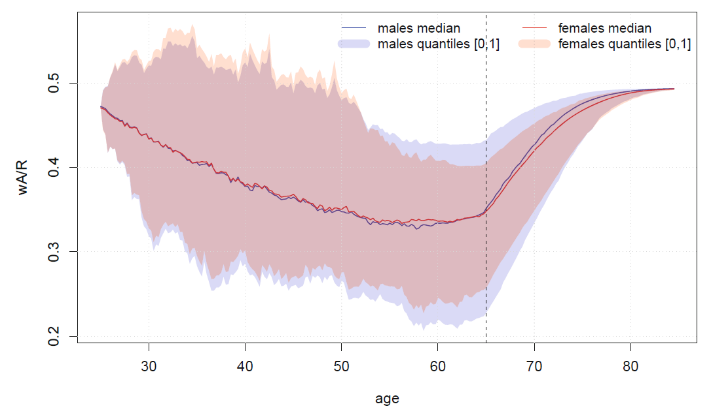


図 10　最適ポートフォリオの富に占めるリスク資産の富（左図），修正富に占める割合（右図）

次に，株・10年国債・長寿債券のそれぞれについてファンドの富に占める割合を確認する．まず，株については図 11の通りである．富および修正富に対する割合は退職後，一定値に収束している．これは退職後であれば労働収入に対するリスクをヘッジする必要がないためである．

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図 11　株式が富に占める割合（左），修正富に占める割合（右）

富に占める10年国債の割合は，図 12の通りである[[8]](#footnote-8)．特徴としては以下の点があげられる．

* 退職前については女性の方が富に占める債券の割合が高く，退職直前で男性の方が高くなる．
* パス間の変動は男性の方が小さい．
* 退職前には女性・男性ともに債券をロングする必要があるが，退職直前でショートしている．

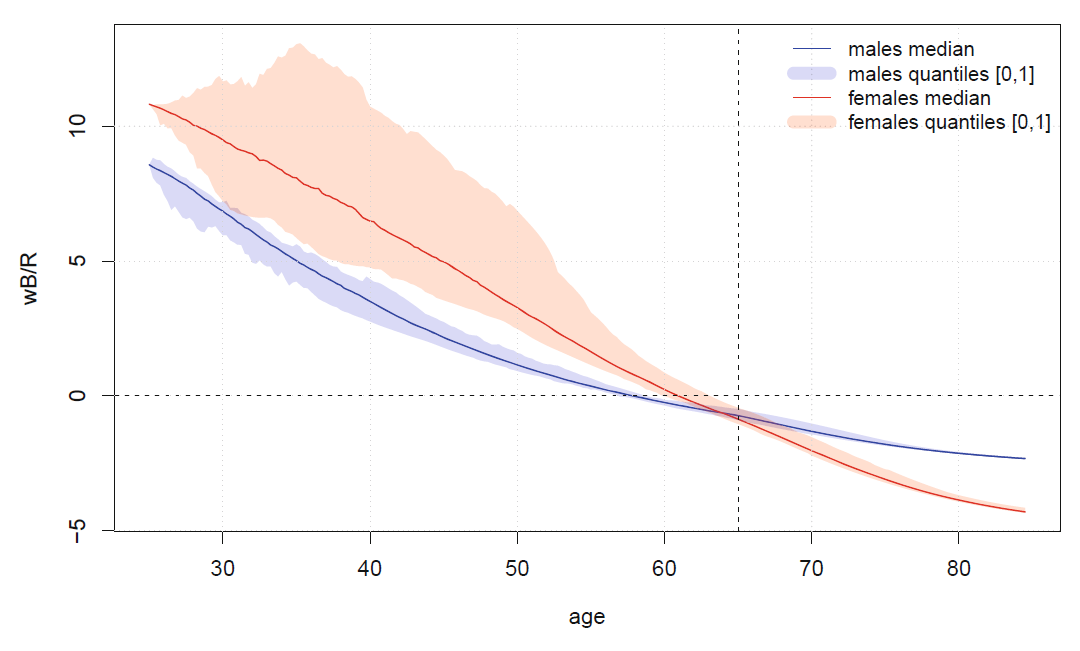


図 12　富に対する10年国債の割合

最後に長寿債券に関するシミュレーション結果を確認する．特徴としては以下の通りである．

* 初期においては女性・男性ともに割合が負であり，退職の数年前に正になる．
* パス間の変動は男性の方が小さい．

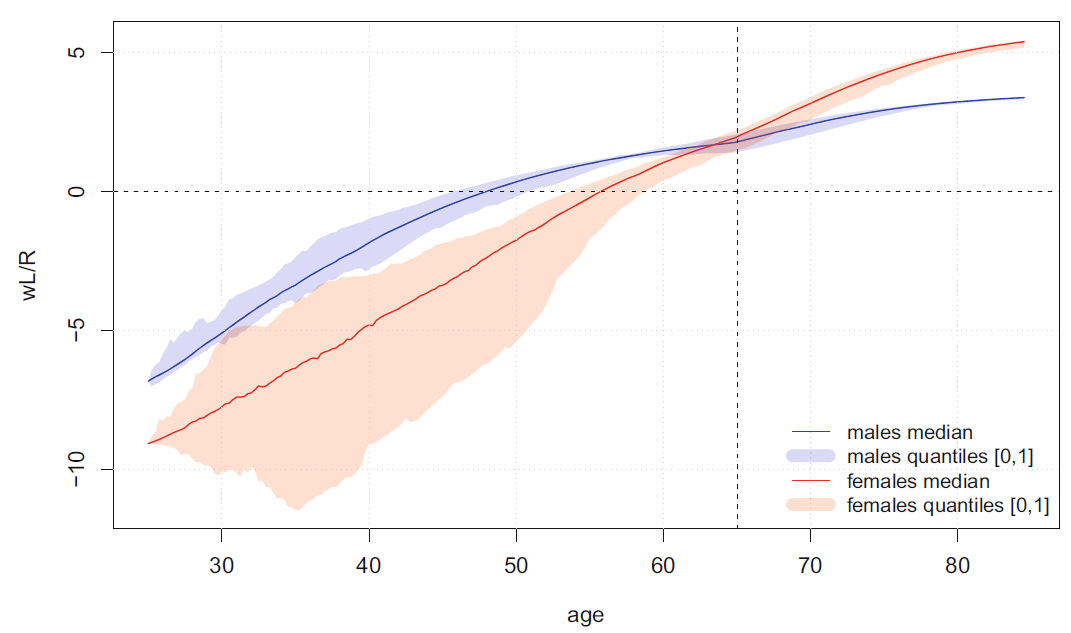


図 13　長寿債券の富に対する割合

これにより，世代間で長寿債券を売買する余地があることがわかる（若い年代の人は長寿債券をショートし，高齢の方は長寿債券をロングするため．）．したがって，保険会社やその他の機関投資家はそれぞれの年代の人をマッチングさせることで需要と供給の両者を見つけることができる．

1. 死力という言葉自体は，企業の倒産確率等の文脈でも使用される． [↑](#footnote-ref-1)
2. feasible conditionは将来の保険料の現在価値と年金の現在価値を等しいとする条件である，この条件を置くことで，金利と死力が定数の場合，以下の式が導ける． [↑](#footnote-ref-2)
3. [↑](#footnote-ref-3)
4. 保険料をこの形の確率微分方程式に限定する理由はPMRをクローズドフォームの形で算出するためである．また，金融市場のリスクに影響を受けるのは，保険料が労働対価に比例し，労働対価はその人を雇用している企業の価値に依存するからである． [↑](#footnote-ref-4)
5. の係数が割引債と同じ値になるのは，とが独立で，二つの債券が同じ満期を持つことを考えれば妥当である．後者の仮定については，任意の満期の債券を複製できる完全市場においてはそれほど強い仮定ではない． [↑](#footnote-ref-5)
6. FRED提供のデータを使用する．１年ごとの値しか取得できないため注意する． [↑](#footnote-ref-6)
7. の推計は生保数理的な資産に流動性がない限り推計が難しい．したがって，多くの論文ではこの値を0としている．しかしながら，この仮定は非現実的であるため，生保数理的な資産はゼロクーポン債で構成され，金利の変化に影響を受けることを考慮し，としている． [↑](#footnote-ref-7)
8. 修正富に対する割合については，その振る舞いが富に対する割合とほとんど変わらない． [↑](#footnote-ref-8)