An Introduction to Premium Setting of Life Insurance Annuities

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Abstract

This paper aims to introduce the reader to the premium setting of annuities within life insurance. This is done using a hypothetical annuity contract offered to 36-year-olds in Sweden. The contract provides an annual pension from age 65 until either the individual’s death or age 90, after which payouts cease. The analysis employs life tables using real-life data to estimate mortality, discounting to decide present values, and calculates fair and risk-adjusted premia for lump sum and annual payment options using theory and simulations. Ultimately, we found that the method used was insufficient given the data. This is due to the last decades’ rise in life expectancy, requiring us to use other methods to acquire accurate premia.

Key Words: Life insurance, annuity, premium setting, pension scheme.

1 Introduction

Annuities are often used in retirement planning to ensure a steady pension after retirement. An annuity is a contract between us (the insurance company) and the person entering the annuity contract (the client). The client will receive payouts starting at a certain age until an agreed upper limit or death. In return, the client must make regular payments, known as premia, during a certain time (Lindholm & Lindskog 2014, pp. 11–12).

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This paper analyses the annuity market in Sweden. We set up a theoretical contract where we offer 36-year-olds the opportunity to receive 100,000 SEK a year if they turn 65 up until they either die or turn 90 after which the payouts stop. To finance this, they can either pay a lump sum premium at 36 or make annual payments. We also risk-adjust the premium to be able to pay the expenses in 99.5 per cent of cases.

Our goal with this report is to calculate the values of the different premia for this situation. To do this, we set up life tables for the population born in 1932 between the ages of 36 and 90 to analyse the mortality for different ages. We then apply it to all 36-year-olds alive in Sweden in 2022. The reason that we chose the 1932 cohort is that they turn 90 in 2022 giving us the most recent data using this method.

2 Theory

2.1 Life Table

A life table shows how the mortality changes for a given age cohort. Let \( \ell_x \) represent the number of people belonging to that cohort alive at age \( x \). It can be calculated recursively using

\[
\ell_{x+1} = \ell_x - d_x,
\]

where \( d_x \) is the number of people in the cohort that died at age \( x \). Let \( q_x \) be the probability that an individual at age \( x \) dies in one year (Lindholm & Lindskog 2014, pp. 8–9). We can estimate \( q_x \) with

\[
\hat{q}_x = \frac{d_x}{\ell_x}.
\]

Using \( \ell_x \) we estimate the survival function (see Section 2.3) and with \( \hat{q}_x \) we simulate annuity contracts.

2.2 Markov Chain

A Markov chain is a stochastic process that describes a sequence of events where the conditional distribution of any future state is independent of the past states and only dependent on the present state (Ross 2019, p. 193). This is the case for our situation. For example, if we want to calculate the probability that a 60-year-old will live to 61, we receive no further information knowing that the person was alive at age 59.
For as long as the individual remains alive, the Markov chain continues moving to new transient states. But when the person dies, the Markov chain ends up in an absorbing state that is impossible to leave. This is an example of an absorbing Markov chain since all ages have a positive probability of death. In fact, this chain is guaranteed to end up in the absorbing state as no human can live forever. We illustrate the situation in Figure 1.

Figure 1: Illustration of the Markov chain for ages $x=0,1,2,\ldots$.

We can express this Markov chain using the following transition matrix, where the first row and column correspond to the (absorbing) dead state:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & \cdots \\
q_0 & 1 - q_0 & 0 & 0 & 0 & \cdots \\
q_1 & 0 & 1 - q_1 & 0 & 0 & \cdots \\
q_2 & 0 & 0 & 1 - q_2 & 0 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots
\end{pmatrix}.
\]

### 2.3 Survival Function

The survival function gives the probability that a person survives past a certain time, $t$. Let $T \geq 0$ be a stochastic variable that represents the age at which the individual dies. Then, the survival function is defined in Lindholm & Lindskog (2014, p. 6) as

\[
S(t) := \mathbb{P}(T > t), \quad t \geq 0.
\]

Using a life table, we can estimate $S(t)$ with

\[
\hat{S}(t) = \frac{\ell_t}{\ell_0}.
\]

We now introduce a conditioned survival function

\[
S_x(t) := \mathbb{P}(T > x + t \mid T > x) = \frac{\mathbb{P}(T > x + t)}{\mathbb{P}(T > x)} = \frac{S(x+t)}{S(x)}, \quad t \geq 0.
\]
Here, \( t \) represents the number of years passed after the person turns \( x \) years old. To estimate \( S_x(t) \) we use the following formula

\[
\hat{S}_x(t) = \frac{\hat{S}(x + t)}{\hat{S}(x)} = \frac{\ell_{x+t}}{\ell_x} = \ell_{x+t}.
\]

### 2.4 Discounting

Discounting is used to determine the present value of forthcoming cash flow (money received or spent in the future). We need discounting because 100 SEK today is not worth 100 SEK in one year. Instead, it is worth less because we can invest the money we have today and increase its value (assuming investments give positive returns). For simplicity, we only invest in risk-free \( t \)-year bonds with a constant annual interest of \( 100R_t \) per cent. This gives us the following discounting function to be (Capiński & Zastawniak 2011, p. 32)

\[
d(t) = (1 + R_t)^{-t}.
\]

### 2.5 Value of Contract

We offer annuity contracts to individuals at the age of \( x \). If they reach the age of \( \nu \), they will receive an annual payout of \( b_t \) until they die or turn \( \tau \), after which the payouts cease. We assume that we immediately learn of a deceased customer. Let \( L \) be the total discounted cost of a single contract. According to Lindholm & Lindskog (2014, pp. 11–12), one annuity contract has the expected (discounted) cost

\[
\mathbb{E}[L] = \sum_{t=\nu-x}^{\tau-x} d(t)b_tS_x(t) \tag{2}
\]

and variance

\[
\text{Var}(L) = \sum_{t=\nu-x}^{\tau-x} d(t)^2b_t^2S_x(t)(1 - S_x(t)) \tag{3}
\]

\[
+ 2 \sum_{t=\nu-x}^{\tau-1-x} \sum_{u=t+1}^{\tau-x} d(t)d(u)b_tb_uS_x(u)(1 - S_x(t)).
\]

Let \( P \) be the total premium paid for one contract. It can either take the form of a single payment made at age \( x \), or \( m \) annual payments of size \( p_t \) so that
\[ P = \sum_{t=0}^{n-1} p_t. \] In the latter case, the first payment will happen at age \( x \) and continue until the person dies or turns \( \nu - 1 \). More precisely,

\[
m = \begin{cases} 
\nu - x & \text{if } T \geq \nu - 1, \\
T - x + 1 & \text{if } T < \nu - 1.
\end{cases}
\]

We call the premium \textit{fair} if \( \mathbb{E}[P] = \mathbb{E}[L] \).

### 2.6 Value of Portfolio

We have \( n \) contracts and call the sum of their costs, \( \sum_{i=1}^{n} L_i \), our \textit{portfolio}. Assume that the costs of all the contracts in the portfolio are independent and identically distributed. Then, the expected cost of this portfolio will be \( \mu = n \cdot \mathbb{E}[L] \) and standard deviation \( \sigma = \sqrt{n \cdot \text{Var}(L)}. \)

Now we include a safety loading to our portfolio and calculate the corresponding premium. The reason for this is to be able to pay the expenses in an absolute majority of cases. Let the expected premium for the total risk-adjusted portfolio be

\[
\mathbb{E} \left[ \sum_{i=1}^{n} P_i^* \right] := \mu + c\sigma,
\]

where \( c \) is a positive constant that determines the size of the safety loading. It is set so that \( \mathbb{P}(\sum_i L_i \leq \sum_i P_i^*) = 1 - \alpha \), where \( \alpha \) is our significance level. If we have a considerable number of contracts, we can – due to the law of large numbers – estimate \( \sum_i P_i^* \) with \( \mathbb{E}[\sum_i P_i^*] \). And if the portfolio can be approximated using the normal distribution, then according to Andersson (2015, p. 15) we find that

\[
\mathbb{P} \left( \sum_i L_i \leq \sum_i P_i^* \right) \approx \mathbb{P} \left( \frac{\sum_i L_i - \mu}{\sigma} \leq c \right) \approx \Phi(c),
\]

where \( \Phi \) is the cumulative distribution function for the normal distribution. This gives us an estimate for \( c \) as

\[
\hat{c} = \Phi^{-1}(1 - \alpha).
\]

Something Lindholm & Lindskog (2014, p. 14) describes as “a reasonable approximation for large portfolios with approximately independent risks.”

### 3 Data

We collect our data from Statistics Sweden (Statistiska centralbyråns 2023a and Statistiska centralbyråns 2023b). The first source gives us a table with the number
of deaths per annum in the age groups 36–90 during the years 1968–2022. From this table we are only interested in the diagonals; the number of 36-year-olds dead in 1968, the number of 37-year-olds dead in 1969, and so on. The second one is a table with two cells corresponding to the number of 36-year-olds alive in Sweden in the years 1968 (89,955) and 2022 (142,871). By applying the model to the entire population, there will be no intra-cohort bias.

To find the number of 37-year-olds alive in 1969, 38-year-olds alive in 1970, et cetera, we use Equation (1). The reason for this is that we must adjust for immigration. Otherwise, the number of people in our age cohort would for some years increase in size. This would lead to negative \(d_x\) and \(q_x\)-values which is absurd.

We assume that the annual interest rate for \(t \in [1, 54]\) is constant and at 3 per cent. The reason we choose 3 per cent is that it is approximately the payoff for purchasing Swedish government bonds ranging from 1 to 50 years according to Nasdaq (2023).

4 Method

We set up the life table (see Table 2 in the Appendix) and used it to estimate the survival function and yearly death probabilities. The portfolio, consisting of 142,871 contracts, is simulated 1,000 times in R to determine its distribution. We also estimate the expected value and standard deviation and compare them to their theoretical counterparts. Furthermore, we analyse the generated cash flow and the age distribution. The fair premia is calculated as well as the risk-adjusted premia with a 99.5 per cent safety loading which is in alignment with the EU insurance regulation Solvency II (Andersson 2015, p. 14).

5 Results

5.1 Value of Contract

The values of the variables defined in previous chapters are \(x = 36\), \(\nu = 65\), \(\tau = 90\), \(R_t = 0.03\) for \(t \in [1, 54]\), and \(b_t = 100,000\) for \(t \in [29, 54]\) and 0 otherwise. Because we have used \(\hat{S}_x(t)\) to estimate the survival function all results have “hats” added to them to indicate that they are estimates. Plugging in our values to (2), we find that the expected cost of an annuity contract in today’s money is

\[
\hat{E}[L] = \sum_{t=\nu-x}^{\tau-x} d(t)b_t \hat{S}_x(t) = 100,000 \sum_{t=29}^{54} 1.03^{-t} \hat{S}_{36}(t) = 526,800 \text{ SEK}.
\]
From the simulations, we found a similar value of 525,596 SEK. Therefore, the fair price for one contract is just over half a million SEK paid upfront today. Undiscounted, this is equal to a cash flow of 1,652,972 SEK. Compare this with the maximum (undiscounted) payout of 2,600,000 SEK (100,000 SEK annually for 26 years).

However, this may not be realistic for most customers who would prefer to pay multiple smaller premia over a longer period. Therefore, we also offer the possibility of paying an annual (constant) premium, $\hat{p}_t$, starting on the person’s 36th birthday and ending on the 64th birthday, for a total of 29 payments. When calculating these payments we adjust for discounting as well as for people dying before 64 and therefore not paying the entire premium. The value of $\hat{p}_t$ can be calculated analogously to the payouts using

$$\hat{p}_t = \frac{526,800}{\sum_{u=0}^{28} 1.03^{-(28-u)} \hat{S}_{36}(u)} = 28,069 \text{ SEK}.$$ 

So, to summarise, the client can either choose to pay 526,800 SEK up front or make 29 annual payments of 28,069 SEK for a total of 814,001 SEK.

We calculate the variance using (3) and find

$$\text{Var}(L) = \sum_{t=\nu-x}^{\tau-x} d(t)^2 b_t^2 \hat{S}_x(t)(1 - \hat{S}_x(t))$$

$$+ 2 \sum_{t=\nu-x}^{\tau-x-1} \sum_{u=t+1}^{\tau-x} d(t)d(u)b_t b_u \hat{S}_x(u)(1 - \hat{S}_x(t))$$

$$= 100,000^2 \sum_{t=29}^{54} 1.03^{-2t} \hat{S}_{36}(t)(1 - \hat{S}_{36}(t))$$

$$+ 2 \cdot 100,000^2 \sum_{t=29}^{53} \sum_{u=t+1}^{54} 1.03^{-t}1.03^{-u} \hat{S}_{36}(u)(1 - \hat{S}_{36}(t))$$

$$= 75,941,392,810 \text{ SEK}^2.$$ 

Thus, the standard deviation for a contract is 275,575 SEK. Not far from the sample standard deviation of 276,175 SEK.

### 5.2 Value of Portfolio

We assume that we have a monopoly on the annuity market in Sweden and that all 36-year-olds purchase our insurance and never cancel it. This gives us for the year 2022 a portfolio of $n = 142,871$ contracts, which we assume to be independent and
identically distributed. This is not unreasonable given the size and composition of our customer base. The expected value of this portfolio is then

\[ \hat{\mu} = n \cdot \mathbb{E}[L] = 142,871 \cdot 526,800 = 75,264,442,800 \text{ SEK} \]

and standard deviation

\[ \hat{\sigma} = \sqrt{n \cdot \text{Var}(L)} = \sqrt{142,871 \cdot 75,941,392,810} = 104,162,482 \text{ SEK}. \]

We now simulate this portfolio 1,000 times. We find that the mean is equal to 75,272,657,953 SEK and the sample standard deviation is 103,575,767 SEK. Both are rather close to their theoretical counterparts.

Now to the safety loading. We want our total premium for all contracts to cover the expenses for the entire portfolio in 199 out of 200 years, that is, \( \alpha = 0.005 \) and \( P(\sum_i L_i \leq \sum_i P_i^*) = 0.995 \). From the simulations we find that we indeed have a sufficiently well approximation of the normal distribution, with \( \sum_i L_i \sim N(\mu, \sigma^2) \).

We confirm this with a Q–Q plot that can be seen in Figure 2.

![Figure 2: Normal Q–Q plot over 1,000 simulated portfolios.](image)

We have \( \hat{c} = \Phi^{-1}(1-\alpha) = \Phi^{-1}(0.995) = 2.576 \). Using (4), this gives us the following risk-adjusted expected premium for the total portfolio

\[ \hat{\mathbb{E}} \left[ \sum_i P_i^* \right] = \hat{\mu} + \hat{c} \hat{\sigma} = 75,264,442,800 + 2.576 \cdot 104,162,482 \]

\[ = 75,532,765,354 \text{ SEK}. \]

Dividing this by \( n \), we find the individual premium including the safety loading to equal \( \hat{\mathbb{E}}[P^*] = 528,678 \text{ SEK} \) (an increase of 1,878 SEK). If the premia are paid annually, the new yearly payments are \( \hat{p}_t^* = 28,169 \text{ SEK} \) (an annual increase of
100 SEK for a total of 2,900 SEK). This corresponds to an increased premium in both cases of 0.36 per cent.

From the simulations, we found three portfolios whose cost exceeded the risk-adjusted premium. This corresponds to 0.3 per cent of all portfolios which is within our confidence level.

5.3 Cash Flow

We illustrate the theoretical undiscounted cash flow of the (fair) premia and payouts made over time in Figures 3–4. Assume that 10 per cent of clients pay the lump sum and the rest choose the annual payment plan. Then we have a large deposit of approximately 11 TSEK at $t = 0$. After that, we see a gradual increase in the cumulative premia paid overtime up to $t = 28$ where the premia payments cease. The premia paid each year slowly decrease as some people die and therefore stop making payments. In total, we generate 106 TSEK in cash flow from the premia.

Then, at $t = 29$, we stop receiving money and instead start making payouts. Similarly, the payouts also decrease with time as more people die. The payouts for the first year are 12 TSEK and the last 4 TSEK. This gives a total negative cash flow of 236 TSEK. The net cash flow is therefore $-130$ TSEK. This difference is completely compensated for thanks to discounting.

![Figure 3: Plot of the theoretical cash flow for $t \in [0, 54]$.](image1)

![Figure 4: Plot of the theoretical cumulative cash flow for $t \in [0, 54]$.](image2)

5.4 The Age Distribution

In Figure 5 below we have a plot of the survival function for our age distribution. As expected it starts at 1 and decreases at an increasing rate with time. For example, we find that \( \hat{S}_{36}(29) = 0.871 \) and \( \hat{S}_{36}(54) = 0.266 \). That is, the probability that a 36-year-old will be at least 65 is 87.1 per cent and at least 90 is 26.6 per cent.
Figure 5: Plot of $\hat{S}_{36}(t)$ for $t \in [0, 54]$.

When simulating the portfolio, we find that 87.2 per cent live to at least 65, meaning they receive at least one payout. We also find that 26.7 per cent live to at least 90, meaning that we pay them the maximum amount of 26 payouts. Both these numbers seem to be correct concerning their theoretical counterparts. The deciles of the age distribution from the simulations can be found in Table 1. There, we can for example see that 50 per cent of the population live to at least 83 years and therefore receive a minimum of 19 payouts.

<table>
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6 Discussion

We used data regarding the death rates for people who were 36 in 1968. Since then, life expectancy in Sweden has changed drastically. Life expectancy for women has increased from 77 years in 1970 to 85 in 2022, and 72 to 81 for men in the same period according to Statistiska centralbyrån (2023c). Due to that, our customers live longer; more people will get a larger number of payouts than is the case using our older data. This affects the result because we will need a higher premium to cover the payouts based on this rise in lifetime expectancy.

In practice, insurance companies use cautious assumptions regarding death rates. This means assuming that people live longer than what the data say. So if this model were to be used in real life today; the survival function would have to be adapted for the current population. This can be done in part by extrapolating the available data we have for people living today to predict when they will die.

An easier – but maybe not as good – improvement, still using only life tables, would be the following: Assume that all 36-year-olds live to be at least 65, instead
of 87 per cent as we found in Section 5.4. Then we would be able to use data that are 29 years more recent. So, instead of working with an age cohort born in 1932, we would look at 1961, a clear improvement to the survival function. In addition to newer data, we would also receive a cautious estimate of the payouts because we assume that all customers would receive at least one payout. In turn, this would lead to a higher lump sum premium which gives us an even better safety loading. The annual premia option, however, would have a smaller change because we would in turn assume all clients make the 29 payments.

Additionally, as an improvement, we could add other costs. For example, adjust for administration and taxes. Assuming we are a profit-driven company, we would also be interested in delivering a profit to the shareholders. This requires us to charge an even greater premium.

Another improvement could have been to use monthly paid premia and payouts instead of annual as this is more realistic. However, it would require us to adapt \( d(t) \), \( q_x \), and \( S(t) \) to work on monthly – instead of yearly – intervals.

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**References**


STATISTISKA CENTRALBYRÅN (2023b) *Folkmängden efter region, civilstånd, ålder
Appendix

Table 2: Life table for people in Sweden born in 1932 over the ages 36–90.

<table>
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