

**Mortality Modelling for Actuarial applications:
Challenges and Implications for Pension
Sustainability and Insurance Pricing**

Author Name: Ms Linda Daly FIA FSAI

Supervised by: Dr Mary Hall



A thesis submitted for the award of PhD

SCHOOL OF MATHEMATICAL SCIENCES

DUBLIN CITY UNIVERSITY

August 2025

Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of PhD is entirely my own work, and that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: Linda Daly

Candidate No: 21261298

Date: 19 August 2025

Dedication

To my parents, who instilled in me the value of education from a young age. Your support have made this journey possible.

Acknowledgements

I would like to express my deepest gratitude to my supervisor, Dr Mary Hall, for her patience, knowledge, and unwavering support throughout this journey. Her guidance and encouragement have been instrumental in this research, and I am truly grateful for her support and supervision.

I would also like to sincerely thank Dr Kevin Hayes, Head of the School of Mathematical Sciences at UCC, for his support in allowing me to take a 1-year research sabbatical to complete my PhD. This leave was invaluable in helping me to reach this milestone.

Finally, I would like to thank my husband Eoin and our three children Fionn, Kate and Caoimhe for their unwavering support and patience throughout the course of this work.

Publications & Contributions

Chapter 2: Mortality in Ireland and Northern Ireland 2000-2021 and the Joint Modelling of Irish and Northern Irish Life Tables

- **Collaborator:** Dr. Mary Hall
- **Publication/Contribution:** European Actuarial Journal, (Daly and Hall (2025))
- **Speaker:** Plenary Session, Society of Actuaries Life Forum, May 2023

Chapter 4: Excess Mortality in Ireland in 2020/2021

- **Collaborator:** Mortality subgroup of Demography Committee of SAI
- **Publication/Contribution:**
 - Lead author of report published on the Society of Actuaries in Ireland website (Daly et al. (2024))
 - Featured on RTE News & Virgin Media News (both national television)
 - Invited speaker on various radio stations, including Ireland's top-rated program, *Morning Ireland*, with a listenership of approximately 500,000

Chapter 4: National Population & Labour Force Projections

- **Collaborator:** Central Statistics Office (CSO) & Mortality Expert Group
- **Publication/Contribution:** Preparation of Official National Population & Labour Force Projections 2023-2057 for Ireland (CSO (2024d))

Contents

1	Introduction	1
1.1	Background	1
1.2	Generalised Additive Models	3
1.2.1	Introduction	3
1.2.2	Background	3
1.2.3	Choice of Distribution for Modelling Mortality Data	5
1.2.4	Generalised Additive Models	7
2	Mortality Trends across Ireland & Northern Ireland	10
2.1	Background	10
2.2	Paper: Mortality in Ireland and Northern Ireland 2000-2021 and the Joint Modelling of Irish and Northern Irish Life Tables	11
2.2.1	Introduction	12
2.2.2	Data	15
2.2.3	Mortality in Ireland and Northern Ireland 2000-2019	16
2.2.4	Joint Mortality Modelling for Ireland and Northern Ireland 2017-2019	20
2.2.5	Impact of Covid-19 on mortality in Ireland and Northern Ire- land in 2020 & 2021	28
2.2.6	Discussion/Conclusion	35
	Appendix: Comparison of Recent Pre-Pandemic Official Life Tables for Ireland and Northern Ireland	39

Appendix 2: Implications of the New Life Tables in Ireland and Northern Ireland	40
2.3 Additional Mortality Trend Measures between Ireland & Northern Ireland	43
2.3.1 Mortality by Cause of Death 2017-2019	43
2.3.2 Premature Mortality	45
2.3.3 European Comparison	47
3 Seasonal Mortality at Older Ages in Ireland	49
3.1 Introduction	49
3.2 Data	53
3.3 Methodology	55
3.3.1 Excess Winter Mortality	55
3.3.2 Seasonal Standardised Mortality Rates (SSMRs)	57
3.3.3 Generalised Additive Models	58
3.4 Results	61
3.4.1 Excess Winter Mortality Index	61
3.4.2 Seasonal Standardised Mortality Rates (SSMRs)	62
3.4.3 Generalised Additive Models	65
3.5 Mortality projections allowing for seasonality	71
3.5.1 Methodology	72
3.5.2 Fitting the model	73
3.5.3 Forecasting using the model	75
3.6 Factors impacting Excess Winter Mortality	79
3.6.1 Excess Winter Mortality by Place of Occurrence of Death	79
3.6.2 Excess Winter Mortality by Marital Status	82
3.7 Discussion	84
Appendix 3.1: Health Spending during the Celtic Tiger Era	87
4 Excess Mortality in Ireland during the Covid-19 pandemic	88

4.1	Background	88
4.2	Paper: Excess Mortality in Ireland during the Covid-19 pandemic . .	91
4.2.1	Introduction	92
4.2.2	Data	94
4.2.3	Age Standardised Excess Deaths in 2020 and 2021	96
4.2.4	Conclusion	101
	Appendix 4.2.1: Gender Specific Excess Mortality	104
4.3	Additional insights on Excess Mortality during 2020 & 2021	109
4.3.1	Simple Excess Mortality in 2020 and 2021	109
4.3.2	Appropriateness of Benchmark period	110
4.4	Population & Labour Force Projections for Ireland 2023-2057	112
4.4.1	Introduction	112
4.4.2	History of Ireland's population	113
4.4.3	Projections 2023-2057	114
5	UK Occupational Pension Scheme Ill-Health Retirement Mortality	
	Experience	120
5.1	Introduction	120
5.2	Data	126
5.2.1	Data by Age Group at Retirement	127
5.2.2	Data by Age Group at Retirement & Pension Band	128
5.2.3	Data by Age Group at Retirement & Industry Sector	130
5.2.4	Data by Age Group at Retirement, Pension Band & Industry Sector	132
5.3	Methodology	133
5.4	One and two factor analysis	134
5.4.1	Preliminary Analysis	135
5.4.2	Analysis of Mortality by Age	136
5.4.3	Analysis of mortality by Age and Pension Band	139
5.4.4	Analysis of mortality by Age and Industry	145

5.5	Analysis of mortality by Age, Pension Band & Industry Sector combined	150
5.6	Conclusion & Discussion	155
	Appendix: Evaluating Differences in Ill-Health Annuity Pricing: Stan-	
	dard S2 Ill-Health Tables versus Customised Rates	158
5.6.1	Male Ill-Health Annuity Values	158
5.6.2	Female Ill-Health Annuity Values	159
6	Mortality Effects of Widowhood	161
6.1	Introduction	161
6.2	Data	162
6.3	Select and Ultimate mortality	167
6.3.1	Modelling the Reverse Select Mortality	170
6.4	Conclusion	173
7	Conclusion	175
7.1	Findings	175
7.2	Limitations	177
7.2.1	Quality of Irish Population Mortality Data	177
7.2.2	Lack of Irish Specific Industry Tables for Actuarial Applications	177
7.3	Future work	178

List of Figures

2.1	Population of Ireland (IRL) and Northern Ireland (NI) by age group (0-29, 30-59, 60-79 and 80-95) for males and females over the period 2000-2021.	16
2.2	Percentage change in population proportions (relative to 2000) by age group (0-29, 30-59, 60-79 and 80-95) and gender (males and females) for Ireland (IRL) and Northern Ireland (NI) over the period 2003-2021.	16
2.3	ASMR for Ireland (IRL) and Northern Ireland (NI) for the 20-year period 2000-2019 for males and females.	17
2.4	Trends in the ASMR for Ireland (IRL) and Northern Ireland (NI) by age group for the period 2000-2019 for males and females.	18
2.5	Relative Mortality Risk (%) between Northern Ireland (NI) and Ireland (IRL) by age group in 2000 and 2019 for males and females respectively.	19
2.6	Annualised mortality improvements by decade and age group for Ireland (IRL) and Northern Ireland (NI) for males and females respectively.	20
2.7	Crude mortality rates for Ireland (IRL) and Northern Ireland (NI) for the period 2017-2019 for males and females respectively.	21
2.8	Ratio of crude mortality rates for Northern Ireland (NI) / Ireland (IRL) for the period 2017-2019 for males and females respectively. . .	22
2.9	Residual plots for the GAMs for modelling the mortality of Ireland and Northern Ireland for males and females respectively.	25

2.10	Partial effects of smooth functions by region for males and females respectively.	26
2.11	Smoothed mortality estimates for Ireland and Northern Ireland for ages 1-120 for males and females respectively.	27
2.12	Total monthly deaths in 2020 for Ireland and Northern Ireland compared to the corresponding average monthly deaths for the period 2017-2019.	29
2.13	Total monthly deaths in 2021 for Ireland and Northern Ireland compared to the corresponding average monthly deaths for the period 2017-2019.	30
2.14	Parameter values from the Lee-Carter models fitted to the pre-smoothed mortality rates for the period 2000-2019 for males and females in Ireland (IRL) including the projected κ_t values for 2020 and 2021. . . .	33
2.15	Parameter values from the Lee-Carter models fitted to the pre-smoothed mortality rates for the period 2000-2019 for males and females in Northern Ireland (NI) including the projected κ_t values for 2020 and 2021.	34
2.16	Mortality rates for ages 0-70 from Irish Life Table 17 for Ireland (IRL) covering the period 2015-2017 and the National Life Table for 2015-2019 for Northern Ireland (NI).	39
2.17	Mortality rates for ages 70+ from Irish Life Table 17 for Ireland (IRL) covering the period 2015-2017 and the National Life Table for 2017-2019 for Northern Ireland (NI).	39
2.18	Comparison of existing life tables for Ireland (ILT17) and Northern Ireland (National Life Table 2015-2017) with the new graduated tables for ages 0-65	40
2.19	Comparison of existing life tables for Ireland (ILT17) and Northern Ireland (National Life Table 2015-2017) with the new graduated tables for ages 65+	41

2.20	Proportion of deaths in Ireland (IRL) and Northern Ireland (NI) for all ages by major cause of death for males and females over the 3-year period 2017-2019.	44
2.21	ASMR in Ireland (IRL) and Northern Ireland (NI) by major cause of death for males and females over the 3-year period 2017-2019.	44
2.22	Proportion of deaths in Ireland (IRL) and Northern Ireland (NI) by major cause of death and age group over the 3-year period 2017-2019 for males and females.	45
2.23	Changes in the ASDR rates for 2020 and 2021 compared to the average ASDR in 2017-2019, for 13 European counties, over the age range 0-99 for males and females respectively.	48
3.1	Annual Mortality Improvements for the 10 years pre, during and post the Celtic Tiger for ages 60–90 for males and females respectively. . .	51
3.2	Exposures for the 32-year period 1986–2017 by age group for males and females respectively.	53
3.3	EWMI plots for age groups 60-69, 70-79, and 80-89 for males and females, respectively, for the three durations 1986-1995, 1996-2005, and 2006-2017.	61
3.4	SSMR's for age groups 60–69, 70–79, and 80–89 for males (—) and females(--) with associated 95% Confidence Intervals (--) from 1986–2016 for Spring, Summer, and Autumn, and from 1986/1987–2016/2017 for Winter.	63
3.5	5-year average annual mortality improvements for males in age groups 60-69, 70-79, and 80-89 during summer (1986-2016) (—) and winter (1986/87 - 2016/17) (—).	64
3.6	5-year average annual mortality improvements for females in age groups 60-69, 70-79, and 80-89 during summer (1986-2016) (—) and winter (1986/87 - 2016/17) (—).	64
3.7	Residual plots for males by season after fitting 2D GAMs.	66

3.8	Residual plots for females by season after fitting 2D GAMs.	66
3.9	Comparison of crude rates (—), SSMRs (—), and fitted GAM rates (—) for ages 65, 75, and 85 for males for the summer over the period 1986-2016 & the winter over the period 1986/87-2016/17. .	67
3.10	Comparison of crude rates (—), SSMRs (—), and fitted GAM rates (—) for ages 65, 75, and 85 for females for the summer over the period 1986-2016 & the winter over the period 1986/87-2016/17. .	68
3.11	Annualised winter mortality improvements from 1986/87–2016/17. . .	70
3.12	Annualised summer mortality improvements from 1986–2016.	70
3.13	M7 residual heat maps for the non-winter data over the age range 60-95 for males and females over the period 1986-2017.	74
3.14	Age effects ($\beta_x^{(i)}$), period effects ($k_x^{(i)}$), and cohort effect (γ_{t-x}) from M7 stochastic model to non-winter data over the age range 60–95 for males and females during 1986–2017.	74
3.15	Projected Kappa plots for non-winter mortality rates from 2018 to 2040, based on the M7 stochastic mortality model, for males and females aged 60-95, with data fitted from 1986 to 2017.	75
3.16	Projected cohort plots for non-winter mortality rates from 2018 to 2040, based on the M7 stochastic mortality model, for males and females aged 60-95, with data fitted from 1986 to 2017.	75
3.17	Seasonal Mortality gap (%) between the annual mortality rate and the non-winter mortality rate for ages 65–90 for males and females, based on data from 2015–2017.	77
3.18	ASMRs in 2040 for various seasonal mortality gap scenarios for males and females respectively.	78
3.19	Relative % change in the ASMR compared to the base annual 2040 projected mortality rate from the M7 model by age group for the 100%, 50%, and 150% seasonal mortality gap scenarios.	79

3.20	Number of Deaths by Place of Death & Age of Death over the 5-year period 2013-2017.	80
3.21	EWMI by Place of Occurrence of Death for age groups 60-69, 70-79, 80-89 and 90-99 over the period 2013-2017.	81
3.22	Percentage of males and females single in Ireland from 1986 – 2016 by age group.	83
3.23	EWMI for those aged 65+ for the years 2015/16 and 2016/17 for males and females respectively.	84
3.24	Public Health Expenditure in Ireland over the period 1990 – 2016. [Data Source (CSO (2015), NISRA (2025b), and CSO (2024))]	87
4.1	Number Of Deaths for age group 0-64 and 65+ over the period 2010-2021.	96
4.2	Population for age group 0-64 and 65+ over the period 2010-2021. . .	96
4.3	Standardised deaths for the period 2010-2021 - standardised relative to the 2021 population.	97
4.4	Comparison of the standardised deaths for 2020 and 2021 with those of the benchmark period shown.	98
4.5	Comparison of the standardised deaths by age group for 2020 and 2021 with those of the benchmark periods shown.	100
4.6	Stringency Index values for 2020 and 2021 for Ireland.	102
4.7	Standardised deaths for males for the period 2010-2021 – standardised relative to the 2021 male population.	104
4.8	Standardised deaths for females for the period 2010-2021 – standardised relative to the 2021 female population.	104
4.9	Comparison of actual and predicted standardised deaths (from simple linear model) for 2020 and 2021 along with the 95% upper and lower prediction intervals.	106
4.10	Comparison of the standardised deaths for the years 2000-2021 for all ages along with the corresponding 3-year benchmark and 95% upper and lower confidence intervals.	107

4.11	Comparison of the standardised deaths by age group for the years 2020 and 2021 with the corresponding 3-year benchmark and 95% upper and lower confidence intervals.	108
4.12	Comparison of the standardised deaths for the years 2000-2021 for all ages along with the corresponding 3-year benchmarks.	111
4.13	Population of Republic of Ireland 1841-2022 [Source:CSO (2025)] . .	114
4.14	Comparison of base table from 2010, 2015 and 2022 population projections.	118
4.15	Projected Population Level 2022–2057 [Source: CSO (2024b).]	119
5.1	Proportion of ill-health retirements by <i>Age Group at Retirement</i> for new retirements over the period 2004-2011 for males and females. . .	127
5.2	Proportion of deaths by <i>Age Group at Retirement</i> over the period 2004-2011 for males and females.	128
5.3	Proportion of male lives by <i>Industry</i> sector	131
5.4	Proportion of female lives by <i>Industry Sector</i>	131
5.5	Crude mortality rates for males and females by individual factor. . . .	135
5.6	Male residual plot from GAMs containing smooth function of <i>Age</i> . . .	138
5.7	Female residual plot from GAMs containing smooth function of <i>Age</i> . .	138
5.8	Mortality rates for males and females by <i>Age Group at Retirement</i> , as modelled by GAMs using smooth function of <i>Age</i> : <55 (—), 55–59 (—), and 60–65 (—).	139
5.9	Male residual plot from GAMs containing smooth functions of <i>Age</i> and <i>Pension Band</i>	142
5.10	Female residual plot from GAMs containing smooth functions of <i>Age</i> and <i>Pension Band</i>	142
5.11	Male mortality rates by <i>Pension Band</i> and <i>Age Group at Retirement</i> . Pension Band 1 is represented by (—), Pension Band 2 by (—), and Pension Band 3 by (—).	143

5.12	Female mortality rates by <i>Pension Band</i> and <i>Age Group at Retirement</i> . Pension Band 1 is represented by (—), Pension Band 2 by (—), and Pension Band 3 by (—).	144
5.13	Male residual plot from GAM containing smooth functions of <i>Age</i> and <i>Industry</i>	147
5.14	Female residual plot from GAM containing smooth functions of <i>Age</i> and <i>Industry</i>	147
5.15	Male mortality rates by <i>Age Group at Retirement</i> and <i>Industry Sector</i> [Public Sector & Local Authority(—) and Private Sector (—)]. When there is no difference in mortality rates between <i>Industry Sector</i> this is represented by (—).	148
5.16	Female mortality rates by <i>Age Group at Retirement</i> and <i>Industry Sector</i> [Public Sector & Local Authority(—) and Private Sector (—)]. When there is no difference in mortality rates between <i>Industry Sector</i> this is represented by (—).	149
5.17	Male residual plot from GAM containing smooth functions of <i>Age</i> , <i>Pension Band</i> , and <i>Industry</i> sector.	152
5.18	Male mortality rates for those who retired before age 55, for each <i>Pension Band</i> shown by <i>Industry Sector</i>	154
5.19	Male mortality rates for those who retired before age 55, for each <i>Industry Sector</i> shown by <i>Pension Band</i>	154
6.1	Graduated rates for males & females from the "S3" SAPS tables for All Pensioners (PML, PFL) and Dependants (DML, DFL) over the age range 70–100.	163
6.2	Number of lives who became dependants during the exposure period (01/01/2009–31/12/2016), shown by <i>Age at Widowhood</i> and gender. .	164
6.3	Distribution of 'Start Pension' amounts for new dependants who entered widowhood during the exposure period (01/01/2009–31/12/2016), by gender.	165

6.4	Crude mortality rates for 1-year reverse select (—) and ultimate (—) mortality rates by gender and <i>Age Group at Widowhood</i> : 50–59, 60–69, 70–79, and 80–89.	168
6.5	ASDRs for the 1-year reverse select period and ultimate period for males and females by <i>Age Group at Widowhood</i> : 50–59, 60–69, 70–79, and 80–89	169
6.6	Select Mortality ASDR / Ultimate Mortality ASDR for males & females for <i>Age Group at Widowhood</i> : 0–59, 60–69, 70–79, and 80–89. .	170
6.7	Crude 1-yr reverse select mortality rates for male & female dependants along with the corresponding relative risk for ages 50-90.	170
6.8	Residual plot for the GAM for modelling male and female 1-year reverse select mortality.	172
6.9	Partial effects of smooth functions for ages 55-90.	172
6.10	Smoothed 1-year reverse select mortality rates for males and females for ages 55-90.	173

List of Tables

2.1	Parameter values for the GAMs for modelling the mortality of Ireland and Northern Ireland for males and females respectively	24
2.2	Parameter values for the Kannisto models and goodness of fit results.	27
2.3	Life Expectancy at Birth & Age 65 for Males and Females in Ireland and Northern Ireland	28
2.4	Excess mortality during the Covid-19 pandemic years 2020 and 2021 for Ireland (IRL) and Northern Ireland (NI), where the expected deaths were calculated using the 2017–2019 life table mortality rates.	31
2.5	Results of fitting the 2-D GAMs to ages 0-95 for years 2000-2019 for smoothing the mortality trends for Ireland and Northern Ireland prior to fitting the Lee-Carter model.	32
2.6	Excess mortality during the Covid-19 pandemic years 2020 and 2021 for Ireland (IRL) and Northern Ireland (NI), where the expected deaths are based on mortality projections from the Lee-Carter model applied to pre-smoothed mortality rates for 2000-2019.	35
2.7	Comparison of annuity rates at age 65, assuming a fixed 3% p.a. interest rate, between the periods 2015–2017(Existing Table) and 2017–2019 (New Table). The Existing Life Table is titled ILT17 for Ireland National Life Table 2015-2017 for Northern Ireland.	41

2.8	Comparison of annuity rates at age 65, assuming a fixed 3% p.a. interest rate, between the periods 2001–2003 and 2017–2019 (New Table). The 2001–2003 table is titled ILT14 for Ireland and National Life Table 2001–2003 for Northern Ireland.	42
2.9	The YPLLI for males and females in Ireland & Northern Ireland for 2017-2019 (averaged), 2020 and 2021	47
3.1	Change in exposures from 1986 to 2017 by age group for males and females respectively.	54
3.2	Seasons and corresponding months	54
3.3	EWMI values for age groups 60-69, 70-79, and 80-89 for males and females across the periods shown.	62
3.4	Annualised summer and winter mortality improvements for males and females by age group for the period 1986-2016 (summer) and 1986/87-2016/17 (winter).	65
3.5	Parameter values and goodness of fit statistics for the 2D GAMs used to smooth seasonal mortality rates for males in Ireland.	66
3.6	Parameter values and goodness of fit statistics for the 2D GAMs used to smooth seasonal mortality rates for females in Ireland.	66
4.1	Average Annual Standardised Deaths for the benchmark periods listed.	97
4.2	Excess deaths in 2020 and 2021 (adjusted for population differences) relative to the benchmark period 2017–2019.	99
4.3	Excess deaths in 2020 and 2021 (adjusted for population differences) by age group relative to the benchmark period 2017–2019.	101
4.4	Excess male deaths in 2020 and 2021 (adjusted for population differences) relative to the benchmark period 2017–2019.	105
4.5	Excess female deaths in 2020 and 2021 (adjusted for population differences) relative to the benchmark period 2017–2019.	105

4.6	Comparison of Actual vs Predicted Deaths (using simple linear model) for 2020 and 2021	107
4.7	Excess deaths in 2020 and 2021 (unadjusted for population differ- ences) relative to the average annual deaths over the previous 3-year, 5-year and 10-year periods.	109
4.8	Male annualised mortality improvements in the 3(2017-2019), 4(2016- 2019), and 5(2015-2019) years prior to the pandemic and during the 2020-2022 pandemic period, for age groups 0-90 and 60-90.	115
4.9	Female annualised mortality improvements in the 3(2017-2019), 4(2016- 2019), and 5(2015-2019) years prior to the pandemic and during the 2020-2022 pandemic period, for age groups 0-90 and 60-90.	116
5.1	Deaths & Exposures by <i>Age Group at Retirement</i>	128
5.2	<i>Pension Band</i> thresholds at the 33rd, 66th, and 100th percentiles for males and females.	129
5.3	Deaths & Exposures by <i>Age Group at Retirement</i> and <i>Pension Band</i> over the period 2004-2011 for males and females.	130
5.4	Deaths & Exposures by <i>Age Group at Retirement</i> and <i>Industry Sector</i> over the period 2004-2011 for males and females	132
5.5	Deaths & Exposures by <i>Age Group at Retirement</i> , <i>Pension Band</i> , and <i>Industry Sector</i> over the period 2004-2011 for males and females. . . .	133
5.6	ASDR by <i>Age Group at Retirement</i> for males and females aged 65–85. 137	
5.7	B_0 (intercept) estimates, EDF for smooth function f_1 , and adjusted R^2 values, by <i>Age Group at Retirement</i> and gender, fitted over the specified age ranges.	138
5.8	ASDR by <i>Age Group at Retirement</i> and <i>Pension Band</i> for males and females aged 65–85.	139
5.9	Parameter estimates and corresponding p-values, by <i>Age Group at</i> <i>Retirement</i> and gender fitted over the specified age ranges.	141

5.10	EDF and p-values for each of the smooth terms, shown by <i>Age Group</i> <i>at Retirement</i> and gender fitted over specified age ranges.	141
5.11	Adjusted R^2 values from GAM models including <i>Age</i> and <i>Pension</i> <i>Band</i>	142
5.12	The 20-year survival probability (from age 65 to 85) by <i>Pension Band</i> and <i>Age Group at Retirement</i> for males and females respectively. . . .	144
5.13	ASDR by <i>Age Group at Retirement</i> and <i>Industry Sector</i> for males and females aged 65–85.	145
5.14	Parameter estimates and p-values, by <i>Age Group at Retirement</i> and gender fitted over the specified age ranges.	146
5.15	EDF and p-values for each of the smooth terms by <i>Age Group at</i> <i>Retirement</i> and gender, fitted over the specified age ranges.	146
5.16	Adjusted R^2 values from GAM model including <i>Age</i> and <i>Industry</i> . . .	147
5.17	The 20-year survival probability (from age 65 to 85) by <i>Industry Sec-</i> <i>tor</i> and <i>Age Group at Retirement</i> for males and females respectively .	149
5.18	Estimates and p-values for the main effects, including intercept(B_0), <i>Pension Band</i> , <i>Industry Sector</i> , and the interaction between <i>Pension</i> <i>Band</i> and <i>Industry Sector</i> over the specified age ranges.	151
5.19	EDF and p-values for each of the smooth terms.	152
5.20	AIC and Adjusted R^2 values for models excluding and including <i>In-</i> <i>dustry</i> by <i>Age Group at Retirement</i>	153
5.21	Male Ill-Health annuity factors and % differences (compared to the S2 Male Ill-Health table, S2IMA), by <i>Age Group at Retirement</i> (<55, 55–59, 60–65).	158
5.22	Male Ill-Health annuity factors and % Differences (compared to S2 Male Ill-health table S2IMA) by <i>Age Group at Retirement</i> (<55, 55– 59, 60–65) and <i>Pension Band</i> (PB1, PB2, PB3).	158

5.23	Male Ill-Health annuity factors and % Differences (compared to S2 Male Ill-health table S2IMA) by <i>Age Group at Retirement</i> (<55, 55–59, 60–65) and <i>Industry Sector</i> (Public Sector & Local Authority, Private Sector).	158
5.24	Male Ill-Health annuity factors and % Differences (compared to S2 Male Ill-health table S2IMA) for those who retired <55 by <i>Industry Sector</i> (Public Sector & Local Authority, Private Sector) and Pension Band (PB1, PB2, PB3).	159
5.25	Female Ill-Health annuity factors and % Differences (compared to S2 Female Ill-health table S2IFA) by <i>Age Group at Retirement</i> (<55, 55–59, 60–65).	159
5.26	Female Ill-Health annuity factors and % Differences (compared to S2 Female Ill-health table S2IFA) by <i>Age Group at Retirement</i> (<55, 55–59, 60–65) and <i>Pension Band</i> (PB1, PB2, PB3).	159
5.27	Female Ill-Health annuity factors and % differences (relative to the S2 Female Ill-Health table, S2IFA), by <i>Age Group at Retirement</i> (<55, 55–59, 60–65) and <i>Industry Sector</i> (Public Sector & Local Authority, Private Sector).	160
6.1	Summary Statistics of the S3 Dependant dataset.	164
6.2	Yearly poverty thresholds in 2022/2023 for a single pensioner in the UK. (<i>Data Source: Trust for London (2024)</i>)	165
6.3	Deaths & Exposures by <i>Age Group at Widowhood</i> for the 1-year reverse select period.	166
6.4	Deaths & Exposures by <i>Age Group at Widowhood</i> for the ultimate period.	166
6.5	Parameter values for the GAM for modelling male and female 1-year reverse select mortality.	172

Abstract

PhD Title: Mortality Modelling for Actuarial applications: Challenges and Implications for Pension Sustainability and Insurance Pricing

Name: Linda Daly

Mortality forecasting and longevity risk are critical concerns for insurers, employers offering occupational pension schemes, and governments providing state pensions and social welfare benefits. Moreover, as many countries, including Ireland, experience an ageing population, increased longevity raises pension costs, potentially undermining the sustainability of funding models used by both Companies and the state. However, accurately estimating mortality rates and forecasting future trends remains a significant challenge. For instance, the SARS-CoV-2 pandemic had a profound impact on mortality rates from 2020-2022 with potential long-term effects. While the death toll of a country often serves as the ultimate indicator of pandemic impact, the calculation of excess deaths (deaths beyond expected levels) is complex and subjective. Seasonal mortality variations also pose risks, with factors such as climate change, medical advances, and improvements in living standards disrupting established patterns, adding uncertainty for insurers and policymakers. Accurate mortality estimation for those retiring due to ill health is another complex issue. Ill-health retirement rates increase with age and are higher for females. As pension schemes raise retirement ages in line with increasing life expectancy and more females join the workforce, the mortality of ill-health retirees will become increasingly important. This is an especially important consideration for employers providing occupational pensions and insurers providing insurance for these benefits and/or selling impaired life annuities. Modelling these mortality challenges is particularly difficult for smaller populations, where mortality rates can be highly volatile. In Ireland and Northern Ireland, current national life tables have shown inconsistent patterns, lack regional coherence, and exhibit volatile mortality trends. By jointly modelling mortality across different populations, the accuracy and coherence of forecasts can be improved. Joint modelling, or multi-population modelling, enhances the robustness of final graduated rates by allowing populations to borrow strength from each other. This thesis provides insights into these evolving mortality challenges, contributing to more informed decision-making and ultimately improving the long-term sustainability of pension schemes (both private and public) and increasing the offering of accurately priced pension products.

Chapter 1

Introduction

1.1 Background

As the population ages, the demand for resources by the elderly will rise, placing significant pressure on both public and private finances. Longevity risk, the possibility that individuals live longer than expected poses a significant challenge for life insurers, pension providers and governments. When life expectancy is underestimated, it can lead to insufficient reserves to cover long-term payouts (Bayraktar et al. 2009). Therefore, accurate models of current and future mortality are vital for managing insurers and pension providers long-term financial obligations.

While global life expectancy has continued to rise, the rate of improvement has slowed in wealthier nations, particularly in Europe. Factors such as rising obesity, heart disease, and an aging population have contributed to this deceleration (Marmot, Stansfeld, Patel, et al. (2020), Wise (2025), Office for National Statistics (2021), and Kabir and O'Brien (2023)). A recent study highlights that environmental factors such as socio-economic status, lifestyle, and healthcare access now play a more significant role in longevity than genetics (Argentieri et al. (2025)). Specifically, these environmental influences, including both lifestyle choices and living conditions, are estimated to be about ten times more important than genetics in determining healthy aging and risk of premature death. Furthermore, this study found that the combined effects of age, sex, and environmental factors account for

approximately 66% of mortality risks. Separately, in the United States, recent trends indicate declines in life expectancy, driven by factors such as opioid overdoses and chronic diseases (Case and Deaton (2020) and Ruhm (2018)).

Emerging demographic challenges, such as declining birth rates coupled with ageing populations significantly impacts longevity risk management. As people live longer, pension systems face greater strain due to longer payout periods whereas fewer younger people entering the workforce create challenges for funding these obligations. For example, Ireland is ageing at the fastest rate in Europe, and those aged 65+ has grown by 35% over the past decade and more than three times the rate of growth in the overall population (Department of Health, Ireland (2024)). Meanwhile Irish births are down by 20% (Journal (2024)). This demographic shift will exert considerable financial pressure on the sustainability of the public sector pension scheme which is operated on a pay-as-you-go systems.

Risk based regulatory regimes have also impacted on longevity risk management for insurers. Under Solvency II, the mortality shock allowance is a standard stress scenario that assumes a permanent 15% increase in mortality rates across all ages (European Commission (2015)). It ensures insurers hold sufficient capital to cover higher-than-expected death claims under life insurance contracts (EU (2009) and European Union (2015)). The EU's IORP II regulation, effective since January 2022, emphasis's the necessity for pension schemes to manage all risks including longevity risk (Pensions Authority (2025)). It requires governance, actuarial assessments, and transparency, ensuring that schemes are well-prepared for the risk posed including that of increasing life expectancy (EIOPA 2025). Furthermore, as the outstanding liabilities of DB pension schemes mature, more schemes will approach their end-game funding objectives, whether through self-sufficiency or a buy-out. During this transition, as investment risk declines, longevity risk is likely to become a more prominent component of overall scheme risk (L&G 2016). Consequently, accurate mortality modelling has become increasingly important.

Longevity risk management in Ireland is hampered by the limited analysis and

modelling of Irish mortality to date. This thesis attempts to address this by investigating mortality trends and the factors affecting mortality in Ireland and Northern Ireland. Risk management for pension scheme requires an understanding of all categories of pension scheme members. This thesis also analyses and models the mortality of ill-health and dependant pensioners.

1.2 Generalised Additive Models

1.2.1 Introduction

Throughout this thesis, Generalised Additive Models (GAMs) have been extensively used as the primary modelling technique. GAMs offer a flexible approach to capturing complex, non-linear relationships within data, making them particularly well-suited for mortality modelling where factors such as age, time, and seasonal effects can interact in different ways (Wood (2006), Hall and Daly (2016), and Müller, Jürges, and König (2006)). This section provides an introduction to GAMs, explaining their underlying methodology and highlighting the reasons they are especially effective for modelling mortality trends and patterns. By allowing smooth functions to model predictor variables, GAMs can accommodate subtle variations in mortality rates, which traditional linear models may fail to capture adequately (Booth and Tickle (2008) and Wood (2006)). Given GAMs are extensions to Generalised Linear Models (GLM's), the basic principles of linear and GLMs are first reviewed, followed by an extension to the framework of GAMs.

1.2.2 Background

Linear models are statistical models in which a univariate response is modelled as the sum of a 'linear predictor' and a zero mean random error term (Wood (2006)). Predictor variables associated with the response variable are combined with unknown parameters (estimated from the data) to enable prediction. GLMs (Nelder and Wedderburn (1972)) extend traditional linear models by relaxing two important

assumptions:

- The assumption of a normally distributed response variable is relaxed. Instead, GLMs allow the response variable to follow any distribution from the *exponential family* (e.g., normal, binomial, Poisson, gamma). This flexibility allows GLMs to model a wide variety of response types including counts, proportions, and binary outcomes.
- The strict linearity assumption between predictors and response is relaxed. GLMs assume that the expected value of the response variable is related to a linear combination of predictors via a *link function*, which is a smooth, monotonic, and differentiable function (McCullagh and Nelder (1989a)).

A GLM consists of three components:

1. Random component: The distribution of the response variable, assumed to come from the exponential family.
2. Systematic component: A linear predictor of the form

$$\eta_i = \mathbf{x}_i^\top \boldsymbol{\beta}, \quad (1.1)$$

where $\mathbf{x}_i$ is a vector of covariates and $\boldsymbol{\beta}$ is a vector of coefficients.

3. Link function: A function $g(\cdot)$ such that

$$g(\mu_i) = \eta_i = \mathbf{x}_i^\top \boldsymbol{\beta}, \quad (1.2)$$

where $\mu_i = E[Y_i]$ is the expected value of the response.

The distribution of the response variable Y_i is assumed to come from the exponential family, with probability density (or mass) function:

$$f(y_i; \theta_i, \phi) = \exp \left\{ \frac{y_i \theta_i - b(\theta_i)}{a(\phi)} + c(y_i, \phi) \right\} \quad (1.3)$$

where:

-
- θ_i : the canonical (natural) parameter,
 - ϕ : the dispersion parameter,
 - $a(\cdot), b(\cdot), c(\cdot, \cdot)$: known functions specific to the distribution.

Different GLMs arise from different choices of link functions and distributions:

Model	Response Distribution	Link Function
Linear regression	Normal	Identity: $g(\mu) = \mu$
Logistic regression	Binomial	Logit: $g(\mu) = \log\left(\frac{\mu}{1-\mu}\right)$
Poisson regression	Poisson	Log: $g(\mu) = \log(\mu)$
Gamma regression	Gamma	Inverse: $g(\mu) = 1/\mu$

1.2.3 Choice of Distribution for Modelling Mortality Data

Poisson Distribution

The Poisson distribution is specifically designed to model counts of events occurring independently within a fixed interval of time or space, making it the standard choice for modeling death counts in epidemiological and demographic studies (Clayton and Hills (2013)). It assumes that the mean and variance of the response are equal—a property known as equidispersion.

Owing to its suitability for modeling rare, independent death events over fixed intervals, the Poisson model has been widely adopted by actuaries, epidemiologists, and demographers alike. It is routinely employed in large-scale mortality studies, including those conducted by the Continuous Mortality Investigation (2017; 2018; 2021). Despite its widespread use, the Poisson model’s equidispersion assumption is often violated in practice—particularly at older ages, where empirical data tend to exhibit overdispersion (Macdonald, Richards, and Currie (2018)).

In mortality modeling, the *force of mortality* μ_x (or hazard rate) represents the instantaneous rate of death at exact age x , whereas the *mortality rate* q_x denotes the probability of death between ages x and $x + 1$. Although related by $q_x \approx 1 - e^{-\mu_x}$, they serve distinct modeling roles. The Poisson model typically models

the force of mortality directly, which provides a continuous-time framework favored in recent actuarial literature (Haberman and Renshaw (2011) and Dickson, Hardy, and Waters (2013)). Conversely, some traditional actuarial approaches, such as life table methods, work directly with annual death probabilities q_x (Andersen et al. (1993)).

The Poisson model for mortality assumes the number of deaths $D_{x,t}$ at age x and time t follows a Poisson distribution:

$$D_{x,t} \sim \text{Poisson}(E_{x,t}^c \cdot \mu_{x,t})$$

where:

- $D_{x,t}$ is the observed number of deaths,
- $E_{x,t}^c$ is the central exposed to risk,
- $\mu_{x,t}$ is the force of mortality.

Binomial Distribution

The binomial distribution can also be used to model mortality data but under more constrained circumstances. Specifically, the binomial model is appropriate when each individual in a finite population is subject to a binary outcome such as survival or death and the total number of individuals at risk (i.e., the number of trials n) is known. For example, in a clinical trial with n patients, where each patient either survives or dies within a fixed period, the number of deaths Y can be modeled as $Y \sim \text{Binomial}(n, p)$, where p is the probability of death.

The Binomial model for mortality assumes the number of deaths $D_{x,t}$ at age x and time t follows a Binomial distribution:

$$D_{x,t} \sim \text{Binomial}(E_{x,t}, q_{x,t})$$

where:

-
- $D_{x,t}$ is the observed number of deaths during the period,
 - $E_{x,t}$ is the initial number of individuals exposed to risk at the start of the period,
 - $q_{x,t}$ is the probability of death during the period.

However, in many observational settings, the population at risk may not be fixed or clearly defined, or the number of individuals may be large and the probability of death small. In such cases when n is large and p is small, the binomial distribution can be well approximated by the Poisson distribution making Poisson models more computationally convenient and interpretable for mortality data (Clayton and Hills (2013)).

1.2.4 Generalised Additive Models

GAMs extend GLMs by allowing the linear predictor to include smooth functions of the covariates. By relaxing the linearity assumptions of GLMs, GAMs can capture complex relationships while still retaining a simple linear structure among the predictor variables. Furthermore, two-dimensional smooth functions enable the joint modelling of covariates, allowing interactions to be represented flexibly within the model. The general form of GAM is as follows:

$$g(E[Y \mid \mathbf{X}]) = \beta_0 + \sum_{j \in L} \beta_j x_j + \sum_{k \in S} f_k(x_k) \quad (1.4)$$

where:

- Y is the response variable,
- $\mathbf{X} = (x_1, \dots, x_p)$ is the vector of predictors,
- $g(\cdot)$ is a known link function that relates the expected value of Y to the predictors,

-
- β_0 is the intercept,
 - $\sum_{j \in L} \beta_j x_j$ represents linear (non-smooth) terms,
 - $\sum_{k \in S} f_k(x_k)$ represents smooth functions of predictors, estimated using splines or other smoothing techniques,
 - L and S partition the set of predictors: $L \cup S = \{1, \dots, p\}$ where p is the number of predictor variables.

Various smoothers can be used to estimate the functions f_j in GAMs, including cubic splines, B-splines, natural splines, thin plate splines and thin plate regression splines (Wood (2003) and Wood (2006)). In this thesis, the smooth functions are implemented using thin plate regression splines. Unlike other spline-based smoothing methods, thin plate regression splines avoid the need to specify knot locations and naturally extend to multi-dimensional covariates (Hall and Friel (2011), Hall and Daly (2016), Wood (2003), and Wood (2006)). The degrees of freedom (DOF) in the model specification determine the smoothness of the smooth functions. When specifying the DOF for a smooth function in a GAM a trade-off is needed between a sufficiently high DOF to correctly capture variations in the data and a low DOF to allow the overall trend in the data to be modelled. The models were fitted using penalised maximum likelihood where the model likelihood is modified by the addition of a penalty for each smooth function penalising its “wiggleness”. Each penalty is multiplied by an associated smoothing parameter which controls the trade-off between goodness of fit and smoothness. The application of the penalties during fitting reduces the DOF in the model specification to yield the effective DOF for the smooth functions. The smoothing parameters are estimated automatically from the data. The DOF in the model specification place an upper limit on the flexibility of a smooth function while the smoothing parameters determine the effective DOF within that limit. The lower the effective DOF the smoother the resulting smooth function will be. The choice of DOF for the smooth functions in the GAM specification is not generally critical as long as they are sufficiently large to model

the underlying smooth structure as the penalisation process determines the effective DOF. Further details on specifying smooth functions for GAMs can be found in Hall & Friel (2011). The appropriateness of the DOF can be checked by extracting and smoothing the deviance residuals with respect to the covariates but using significantly increased DOF to ensure that there is no pattern in the residuals that could be explained by increasing the DOF (Wood (2006)). Throughout this thesis GAMs have been implemented using R package *mgcv* (Wood (2001a)) This provides a range of functions for fitting GAMs and checking the model fit.

In summary, GAMs provide a flexible extension to GLMs by allowing non-linear relationships between predictors and the response variable through smooth functions. An essential characteristic of mortality rates is their smooth progression from one age to the next. However, raw mortality data often contain irregular fluctuations due to random variation or sparse observations which can lead to unrealistic age to age jumps if modelled directly. The smoothness constraints in GAMs help to regularise the fitted mortality curves, enforcing gradual changes across ages and time, preventing overfitting to noisy data, and ensuring realistic, stable estimates essential for constructing life tables (Currie (2004) and Wood (2017)). Smooth functions in GAMs facilitate capturing gradual mortality trends and cohort effects, which are important for actuarial and demographic applications (Camarda (2008)). In contrast, GLMs require explicit specification of the functional form of covariates, often leading to rigid or piecewise approximations that may miss important subtleties in mortality data (Wood (2017), Currie, Durban, and Eilers (2004), and Currie (2006)).

Chapter 2

Mortality Trends across Ireland & Northern Ireland

2.1 Background

Despite being part of the same island, Ireland and Northern Ireland are governed separately, with Ireland operating as an independent state and Northern Ireland forming part of the United Kingdom. This distinction has led to notable differences between the two regions in areas such as healthcare systems, pension structures, and broader demographic characteristics. This chapter examines the variation in mortality rates between Ireland and Northern Ireland, and introduces a novel methodology for co-modelling the mortality of both regions. The chapter is structured as follows:

- Section 2.2 presents a published paper, for which I was the lead author on the joint modelling of Irish and Northern Irish Life Tables (Daly and Hall (2025)).
- Section 2.3 presents additional mortality measures (not covered Section 2.2) between Ireland & Northern Ireland.

2.2 Paper: Mortality in Ireland and Northern Ireland 2000-2021 and the Joint Modelling of Irish and Northern Irish Life Tables

Abstract

Mortality assumptions for actuarial applications in Ireland and Northern Ireland are typically set by reference to national life tables or industry specific life tables of the Continuous Mortality Investigation of the Institute & Faculty of Actuaries, UK. Recent national life tables for Ireland and Northern Ireland are poor exhibiting unreasonable mortality patterns, volatile mortality rates, terminate at relatively low ages and lack coherence between the regions. This paper investigates mortality trends for Ireland and Northern Ireland for 2000-2019 and presents a method for jointly modelling the mortality of the regions over the period 2017-2019. Mortality at younger ages was modelled using Generalized Additive Models (GAMs) where mortality between the regions was implemented using difference smooths, while a Kannisto model was used to model aggregated regional mortality data at older ages. The resulting life tables provide smooth, coherent, region-specific mortality rates which extend well beyond the age range of the current life tables and provide a more appropriate basis for mortality assumptions for actuarial applications. Finally, excess mortality was used to assess the impact of the Covid-19 pandemic on the mortality of both regions for 2020-2021. Small populations experience relatively high mortality volatility which can impact estimates of excess mortality. Hence, excess mortality was calculated by reference to the jointly modelled 2017-2019 life tables and, also, by reference to projected mortality rates for 2020 and 2021 obtained by fitting a Lee-Carter model to pre-smoothed mortality rates for 2000-2019. Two dimensional GAMs were used to pre-smooth the mortality rates.

2.2.1 Introduction

Ireland experienced the largest increase in life expectancy of the EU-15 countries over the period 2000-2019 and overtook life expectancy in Northern Ireland in the early years of the 21st century for the first time since the establishment of the Irish Republic and the partition of Northern Ireland in 1922. Due to the lack of industry specific assurance or pensioner life tables, mortality assumptions for actuarial applications in Ireland and Northern Ireland are typically set by reference to national life tables or the life tables of the Continuous Mortality Investigation (CMI) of the Institute & Faculty of Actuaries, UK. In particular, the mortality assumptions in the Actuarial Standards of Practice (ASPs) issued by the Society of Actuaries in Ireland are specified relative to the national life tables for Ireland. The quality of recent national life tables for both Ireland and Northern Ireland is poor with the life tables exhibiting unreasonable mortality patterns, volatile mortality rates, terminate at relatively low ages and lack coherence between the regions (see Appendix). Jointly modelling mortality rates for related populations can result in improved mortality estimates by borrowing strength across the populations (Li and Lee (2005) and Enchev, Kleinow, and Cairns (2017)). This paper investigates the mortality of Ireland and Northern Ireland in the 21st century and proposes a method for jointly modelling the mortality of the regions to provide improved, region-specific, mortality estimates. The resulting life tables provide smooth, coherent, region-specific mortality rates which extend well beyond the age range of the current, national life tables and provide a more appropriate basis for mortality assumptions for actuarial applications, particularly considering population aging.

The Central Statistics Office (CSO) in Ireland is responsible for producing the national life tables for Ireland, referred to as the Irish Life Tables (ILT), following each census which are held approximately every five years. The most recent table, ILT 17, covers the period 2015-2017 and provides graduated mortality rates by gender for ages 0 to 105 (CSO (2020)). Despite graduation, recent Irish Life Tables (namely ITLT 16 (covering the period 2010-2012) and ILT 17) exhibit fluctuating mortality

rates, particularly at high ages. Annual life tables are produced for Northern Ireland by the Office for National Statistics (ONS), UK and are based on a three-year rolling average of deaths and population estimates for ages 0-100. The annual life tables for Northern Ireland are not graduated and exhibit mortality volatility across the age range. The most recent fully graduated life tables for Northern Ireland cover the period 2000-2002 and hence do not reflect the significant changes in mortality that have occurred since the start of the century. Separately producing life tables for Ireland and Northern Ireland also results in regional mortality estimates which lack coherence. Comparison of Irish Life Table 17 for Ireland and the corresponding national life table for Northern Ireland for the period 2015-2017 showed unrealistic mortality divergence at high ages, particularly for males.

Jointly modelling the mortality of two (or more) populations aims to improve the resulting mortality estimates by exploiting the mortality relationship(s) between the populations. Tang et al (2022) discuss jointly modelling male and female mortality rates using adaptive P-splines to graduate mortality rates for England & Wales. The joint modelling approach allows coherent estimates of male and female mortality rates which benefit from borrowing strength across the sexes at the older ages increasing the robustness of the final graduated rates. As shown by Li and Lee (2005), Cairns et al (2011), Kleinow (2015) and Shi et al (2023), multi-population mortality forecasting has become increasingly common in recent years and aims to improve the coherence and accuracy of mortality forecasts for different populations by jointly modelling their mortality over time. Generalized Additive Models (GAMs) are widely used in mortality modelling (Yang et al. (2012), Hilton et al. (2019), Hall and Daly (2016), and Feng (2022)) and GAMs were used in the graduation of the most recent English Life Table (English Life Table (ELT) No. 17) (Dodd et al. (2018)). This paper extends the use of GAMs for graduating mortality rates by jointly modelling the mortality of Ireland and Northern Ireland using difference models. Difference models are based on relative differences between datasets and can result in more parsimonious models where the differences vary in a sim-

ple way. Mortality rates are graduated for both regions for the period 2017-2019 (i.e. pre-pandemic) to allow life expectancies to be calculated for males and females respectively.

The Covid-19 pandemic triggered the largest mortality shock in Western Europe since World War II (Aburto et al. (2022)) and abruptly halted the mortality improvements of the early decades of the 21st century for Ireland and Northern Ireland. The impact of the pandemic varied across the two regions reflecting differences in the respective government responses to the pandemic. By the end of 2021 reported deaths from Covid-19 in Ireland and Northern Ireland were approximately 6,000 and 4,000 respectively (HPSC (2024) and NISRA (2022)). The overall impact of Covid-19 on mortality, both direct and indirect, is more difficult to quantify and this paper investigates the impact of the pandemic on mortality in Ireland and Northern Ireland by analysing excess mortality for 2020-2021 for the regions. Excess mortality is calculated by comparing the actual deaths in 2020 and 2021 with the expected deaths in the absence of the pandemic. Small populations experience relatively high mortality volatility which can impact excess mortality calculations. To allow for this we calculate the expected deaths for the regions by reference to the jointly modelled life tables for 2017-2019 and also by reference to projected mortality rates for 2020 and 2021 based on smoothed, pre-pandemic, mortality trends. The Lee-Carter model was used to project the mortality rates for 2020 and 2021 for the regions and was fitted to mortality rates for 2000-2019 pre-smoothed using 2-dimensional GAMs. The ultimate effects of Covid-19 on the mortality of the regions will emerge over time as Covid-19 becomes endemic in the population and the effects of long Covid become apparent.

The paper is organised as follows: section 2.2.2 describes the data used in the investigation, section 2.2.3 analyses mortality trends in Ireland and Northern Ireland over the period 2000-2019 in advance of graduating mortality rates for the regions for the period 2017-2019 in section 2.2.4, section 2.2.5 investigates the impact of Covid-19 on the mortality of the regions in 2020 and 2021 while section 2.2.6

concludes with a discussion of the results.

2.2.2 Data

Death and population data for Ireland and Northern Ireland were obtained from the Human Mortality Database as of 06 February 2025 (HMD (2025)). Deaths and population estimates were provided by single year of age and gender for the years 2000 to 2022. The population estimates were effective on the 1st January and mid-year population estimates by gender for Ireland and Northern Ireland for ages 0-100 for the years 2000 to 2021 were obtained by averaging the HMD population estimates across consecutive years.

Both regions experienced a gradual ageing of the population over the period. To illustrate the change in the age structure of the population over the period, Figure 2.1 presents the population by age group (0-29 30-59, 60-79, 80-95) and gender over the period 2000-2021 for each region. Figure 2.2 presents the corresponding change in the population proportions relative to the year 2000 for both regions. For Ireland, the proportion of the population aged 60 and over increased by approximately 6% for males and 4% for females between 2000 and 2021. The corresponding increases for Northern Ireland were approximately 7% for males and 5% for females. The relative difference in population size between the regions also changed over the period with Ireland experiencing a larger population increase compared to Northern Ireland. Northern Ireland represented approximately 31% of the combined population of Ireland and Northern Ireland in 2000 but only 27% of the combined population by 2021.

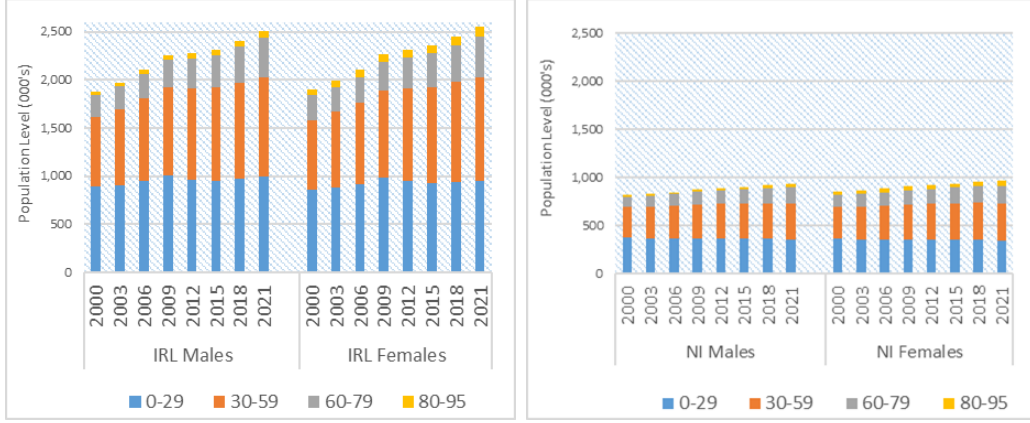


Figure 2.1: Population of Ireland (IRL) and Northern Ireland (NI) by age group (0-29, 30-59, 60-79 and 80-95) for males and females over the period 2000-2021.

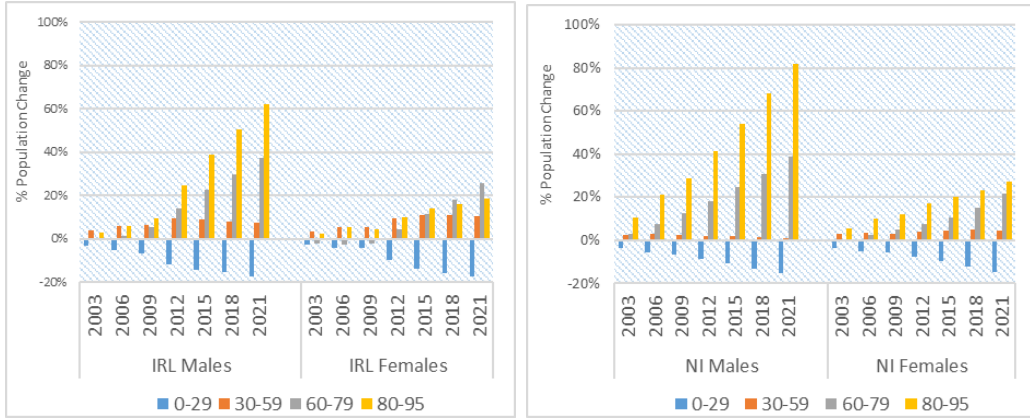


Figure 2.2: Percentage change in population proportions (relative to 2000) by age group (0-29, 30-59, 60-79 and 80-95) and gender (males and females) for Ireland (IRL) and Northern Ireland (NI) over the period 2003-2021.

2.2.3 Mortality in Ireland and Northern Ireland 2000-2019

Mortality in Ireland and Northern Ireland was analysed using directly age standardised mortality rates (ASMRs) standardised to the 2013 European Standard Population (ESP 2013). The ASMR for age group j-k in year t was calculated as follows:

$$d'_{x,t} = \frac{d_{x,t}}{P_{x,t}} \cdot SP_x \quad (2.1)$$

$$ASMR_{j-k} = \frac{\sum_{x=j}^k d'_{x,t}}{\sum_{x=j}^k SP_x} \quad (2.2)$$

where $d_{x,t}$ is the number of deaths aged x in year t , $P_{x,t}$ is the corresponding population and SP_x is the 2013 European Standard Population at age x . The 2013 European Standard Population is provided in five-year age bands and for calculation purposes it was assumed that the population was split equally across all five ages in each age band.

Figure 2.3 presents the trends in the ASMR by region for males and females respectively over the period 2000 to 2019. The ASMR was calculated based on deaths by single year of age to age 94 and for ages 95+ combined. As expected, mortality declined across both regions over the period, though, in general, a levelling off of the mortality decline can be seen in the second decade. At the beginning of the 21st century, Ireland experienced higher overall mortality relative to Northern Ireland. However, a gradual shift transpired over time, leading to lower overall mortality in Ireland for both genders by 2019. This reversal initially manifested among females around 2006 and approximately 10 years later among males around 2016.

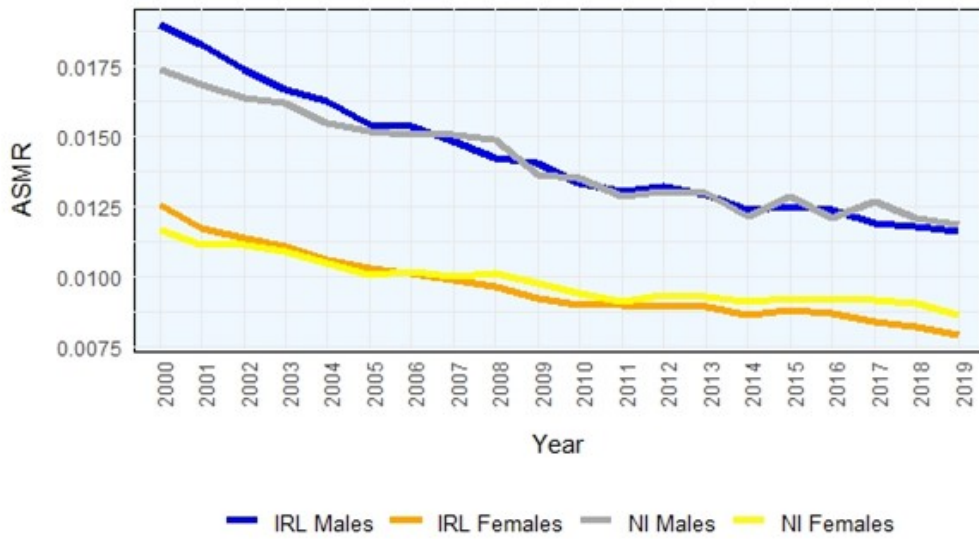


Figure 2.3: ASMR for Ireland (IRL) and Northern Ireland (NI) for the 20-year period 2000-2019 for males and females.

The reversal of the mortality gap between Ireland and Northern Ireland varied by age group. Figure 2.4 presents the trends in the ASMRs for age groups 0-59, 60-79 and 80-95 by region for males and females respectively over the period 2000 to 2019. The levelling off of the mortality decline in the second decade can again be seen in each case with, the exception of the youngest age group, 0-59, in Ireland. At the beginning of the 21st century, Ireland experienced higher mortality across all three age groups relative to Northern Ireland for both males and females. However, by 2019, the situation had reversed for age groups 0-59 and 60-79, with Ireland experiencing lower mortality for both age groups and genders. The reversal in the mortality gap occurred first amongst the youngest age group (0-59) during the early years of the new century, subsequently extending to the age group 60-79 in later years. In general, the mortality gap between the regions for these two age groups widened steadily following the reversal. For the oldest age group, 80-95, for both males and females, the gap between the regions declined steadily over the period with convergence between the regions effectively achieved by the end of the period.

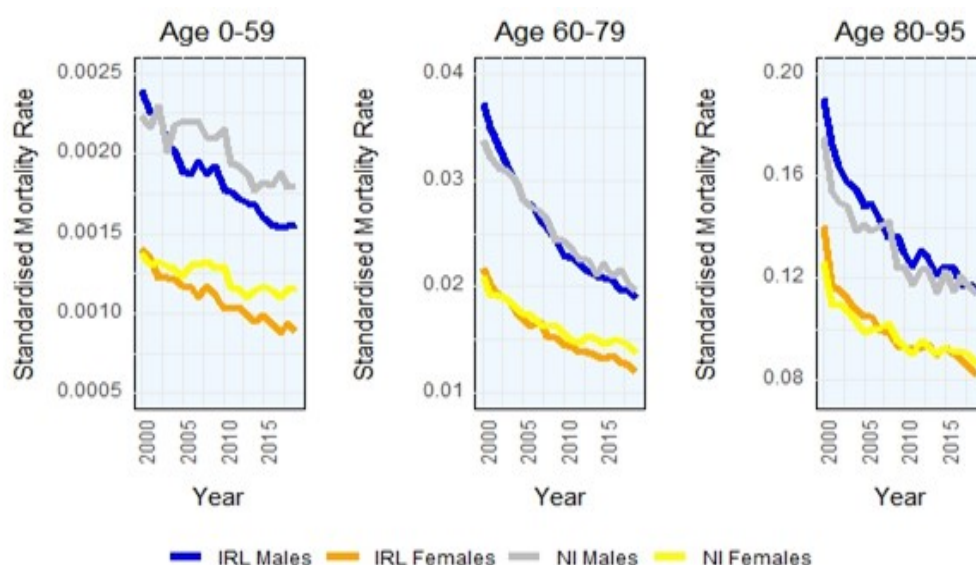


Figure 2.4: Trends in the ASMR for Ireland (IRL) and Northern Ireland (NI) by age group for the period 2000-2019 for males and females.

To summarise the change in the relative mortality between the regions, Figure 2.5 presents the relative mortality risk (%) between Northern Ireland and Ireland in 2000

and 2019 categorised by age group and gender. The reversal in mortality between the regions over the period can clearly be seen for age groups 0-59 and 60-79 with a lower mortality risk in Northern Ireland in 2000 compared to a significantly higher mortality risk in 2019. For age group 80-95, while there was a significant difference in mortality risk between the regions in 2000, this has diminished especially for males where only minor differences exist in 2019.



Figure 2.5: Relative Mortality Risk (%) between Northern Ireland (NI) and Ireland (IRL) by age group in 2000 and 2019 for males and females respectively.

The large relative differences in mortality between the regions in 2019 for the youngest age group is notable. At younger ages suicide is one of the leading causes of death for both males and females with Northern Ireland experiencing a higher suicide rate than both Ireland and the other UK regions (NISRA (2025a) and Samaritans (2019)). The reasons for the high suicide rate in Northern Ireland are complex but are linked to the enduring legacy of the conflict referred to as “The Troubles” (1968-1998). Recent research has highlighted the high levels of post-traumatic stress disorder, transgenerational conflict related trauma and ongoing sectarianism in Northern Ireland in explaining the region’s persistently high suicide rate (O’Connor and O’Neill (2015) and O’Neill and O’Connor (2020)) and ultimately relatively high mortality rate at younger ages.

Mortality improvements varied over the period and Figure 2.6 presents the average annualised mortality improvements by age group over the first two decades of the 21st century for both regions. In general, Ireland experienced higher mortality improvements relative to Northern Ireland in both decades with the exceptions showing relatively similar improvements between the regions. Mortality improvements were noticeably lower in the second decade, with the exception of the youngest age group in Northern Ireland which experienced minimal improvements in mortality during the first decade of the century.

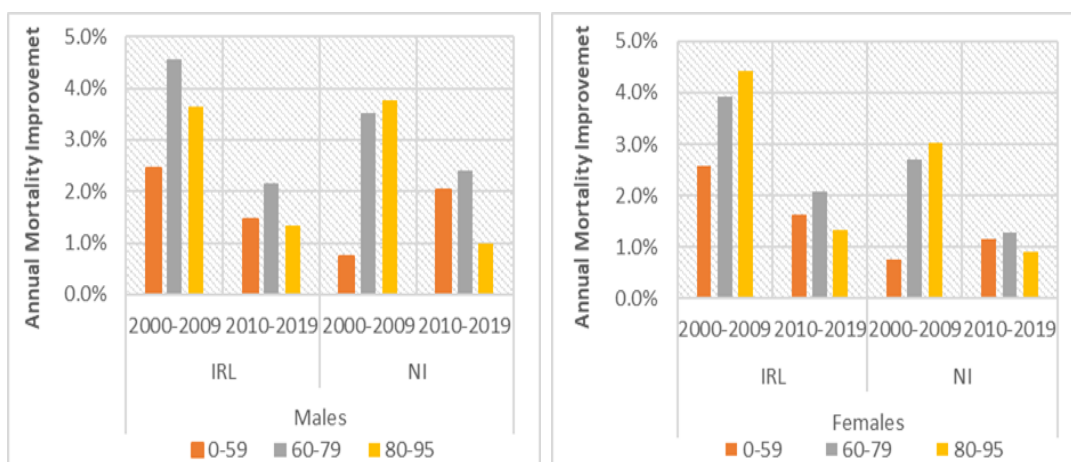


Figure 2.6: Annualised mortality improvements by decade and age group for Ireland (IRL) and Northern Ireland (NI) for males and females respectively.

2.2.4 Joint Mortality Modelling for Ireland and Northern Ireland 2017-2019

A hybrid approach was used to jointly graduate the mortality rates for Ireland and Northern Ireland for the period 2017-2019. For the majority of the age range, where there was sufficient data to allow a semi-parametric smoothing approach to be adopted, a Generalized Additive Model (GAM) was fitted to the data to obtain smooth mortality estimates. At older ages, where the data is sparser, a parametric Kannisto model was fitted to the data to obtain smooth estimates of the mortality rates and to extrapolate beyond the fitted data. Mortality at ages under 1 is typically derived independently when constructing life tables and was excluded

from this analysis.

Figure 2.7 plots the crude mortality rates for ages 1-100 for males and females for each region for the period 2017-2019. The crude mortality rates for Northern Ireland exhibit greater volatility compared to Ireland due to the lower data volumes. Figure 2.8 plots the corresponding relative difference or ratio of the Northern Ireland to Ireland crude mortality rates for males and females. The relative difference or gap in mortality between Ireland and Northern Ireland is very volatile at young ages where deaths are low for both males and females. For males, the mortality gap between the regions increased in the mid-teens and a clear gap in mortality between the regions can be seen for young adults. The mortality gap starts to narrow steadily from about the late thirties converging by the early eighties. At ages over 90, where data volumes are low, the volatility of the mortality gap starts to increase again. For females, the gap in mortality between the regions tends to increase in childhood followed by a slow but volatile decline until the early 50s. Thereafter, there appears to be a relatively steady decline until the mortality rates converge by the late eighties and early nineties. Again, there is an increase in the volatility of the mortality gap from about the mid-90s as data volumes drop at later ages.

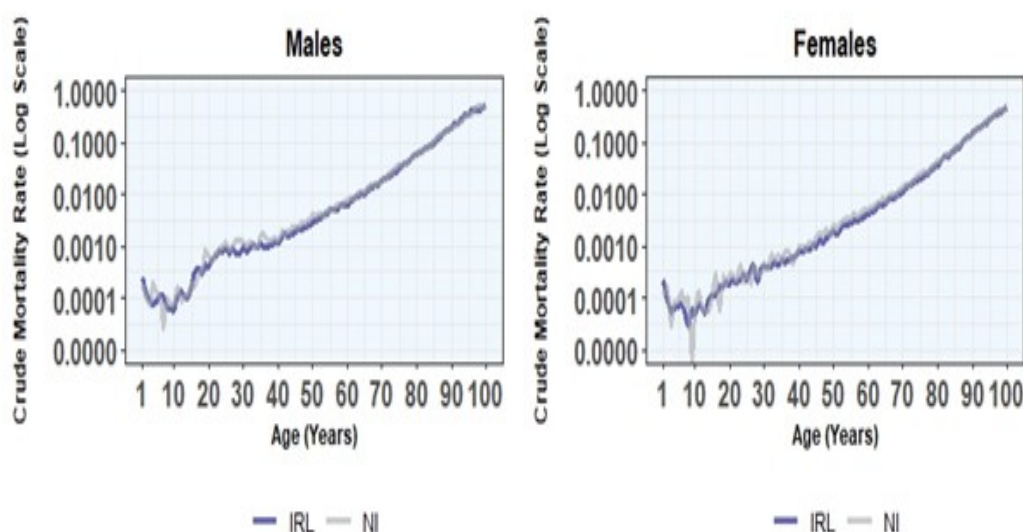


Figure 2.7: Crude mortality rates for Ireland (IRL) and Northern Ireland (NI) for the period 2017-2019 for males and females respectively.

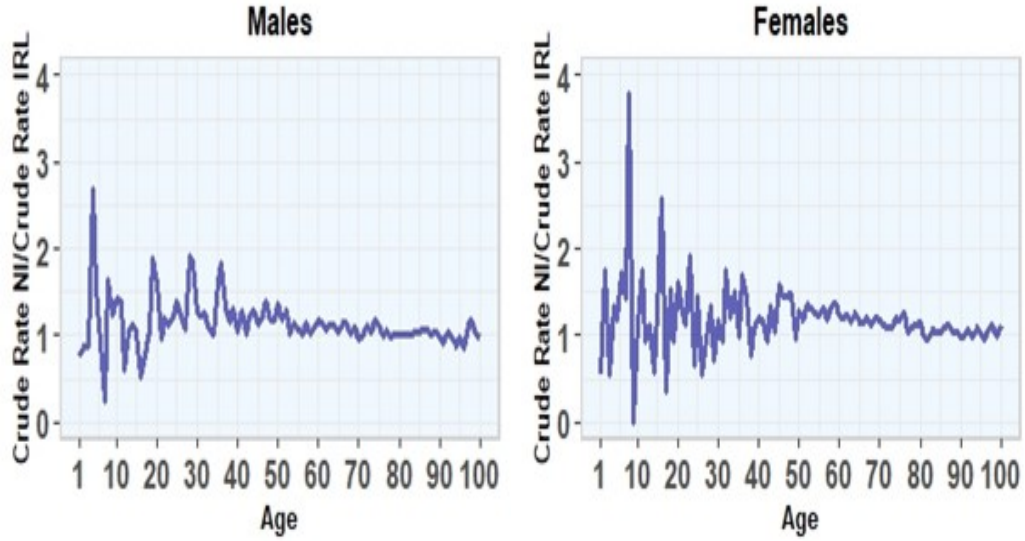


Figure 2.8: Ratio of crude mortality rates for Northern Ireland (NI) / Ireland (IRL) for the period 2017-2019 for males and females respectively.

GAMs extend generalized linear models (GLMs) which model a linear relationship between a non-normal response y and predictors $x_1, \dots, x_n$ by allowing the linear predictor to include smooth functions of the covariates. By relaxing the linearity assumption of GLMs and allowing the linear predictor to include smooth functions of the covariates GAMs allow complex relationships to be implemented while still retaining a simple linear relationship between the covariates. The GAMs were implemented using R (version 4.2.2) library package “mgcv” (version 1.8-41, Wood (2001b)). The R library package “mgcv” allows smooth functions of factor covariates to be implemented as difference smooths which model the differences between the factor levels relative to the baseline or reference factor level. Difference smooths can result in more parsimonious models where the differences between the factor levels vary in a simple way. As discussed, the gap or difference in mortality between Ireland and Northern Ireland was greatest at younger ages and tended to decrease with increasing age. Consequently, it was decided to employ a difference smooth in modelling the mortality of Ireland and Northern Ireland using GAMs. Deaths were assumed to follow a Poisson distribution and the following GAM was fitted to the data for Ireland and Northern Ireland:

$$d_x \sim \text{Poisson}(E_x^c \mu'_x) \quad (2.3)$$

$$\log(\mu'_x) = \beta_0 + \text{Region} + f_1(\text{Age}_x) + f_2(\text{Age}_x, \text{byRegion} = \text{NI}) + \log(E_x^c) \quad (2.4)$$

where d_x represents the number of deaths at age x and E_x^c represents the corresponding central exposed to risk. The central exposed to risk was approximated using the mid-year population estimates. Deaths and populations were aggregated over the three-year period 2017-2019 and μ'_x represents the central mortality rate which approximates the force of mortality, μ , at age $x + 1/2$. Region is a 2-level factor variable with levels Ireland (reference level) and Northern Ireland respectively. f_1 is a smooth function by Age for the reference level of the factor Region i.e., f_1 is a smooth function by Age for the data for Ireland. f_2 is implemented as a difference smooth function which models the mortality of Northern Ireland relative to that of Ireland (the reference level of the factor Region). Mortality rates for smaller populations are inherently more volatile due to lower data volumes hence the choice of Ireland as the reference level smooth with a population more than double that of Northern Ireland. The GAMs were fitted to data for ages 1-90 and separate models were implemented for males and females respectively.

The R library package “mgcv” provides a choice of spline functions for implementing smooth functions. Thin plate regression splines were chosen as unlike other spline-based smoothing functions thin plate regression splines avoid the need to choose “knot” locations (Wood (2003) and Wood (2006)). Hall and Daly (2016) describe implementing GAMs, using thin plate splines, to model pensioner mortality rates. In summary, the degrees of freedom (DOF) in the model specification determine the smoothness of the smooth functions. When specifying the DOF for a smooth function a trade-off is needed between a sufficiently high DOF to correctly capture variations in the data and a low DOF to allow the overall trend in the data to be modelled. The models were fitted using penalised maximum likelihood where the model likelihood is modified by the addition of a penalty for each smooth function

penalising its “wiggleness”. Each penalty is multiplied by an associated smoothing parameter which controls the trade-off between goodness of fit and smoothness. The application of the penalties during fitting reduces the DOF in the model specification to yield the effective DOF for the smooth functions. The choice of DOF for the smooth functions in the GAM specification is not generally critical as long as they are sufficiently large to model the underlying smooth structure as the penalisation process determines the effective DOF.

Table 2.1 presents the final fitted models for males and females respectively, while Figure 2.9 presents the corresponding residual plots. The adjusted R^2 values for both models were 99.9%. When fitting the models, the degrees of freedom for each smooth function are set using the parameter “k” in the smooth function specification. For the final models, the parameter “k” was set to 50 for each smooth. As a check on the degrees of freedom chosen, the models were repeatedly refitted with the “k” values for each smooth set to 60, 70 and 80 in turn. In each case, increasing the specified degrees of freedom had minimal impact on the effective degrees of freedom of the smooth functions. The p-values for all terms, for both males and females, were highly significant (all zero to six decimal places).

	Males	Females
β_0	-5.9181 (0.013)	-6.3738 (0.017)
Region - Northern Ireland	0.1002 (0.017)	0.1186 (0.022)
Effective degrees of freedom for the smooth functions		
$f_1(\text{Age})$ - Ireland	24.384	19.537
$f_2(\text{Age})$ - Northern Ireland	3.643	2.608

Table 2.1: Parameter values for the GAMs for modelling the mortality of Ireland and Northern Ireland for males and females respectively

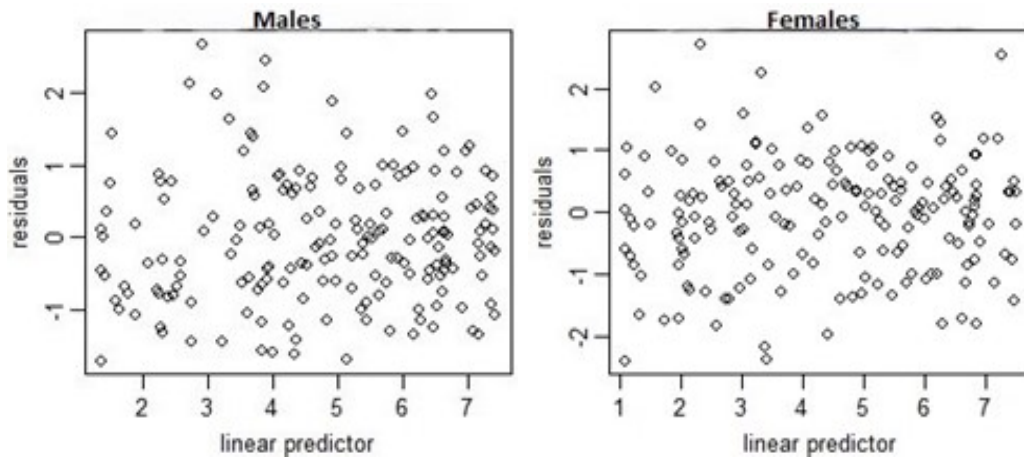


Figure 2.9: Residual plots for the GAMs for modelling the mortality of Ireland and Northern Ireland for males and females respectively.

To illustrate the implementation of the smooth functions Figure 2.10 presents the partial effects of the smooth functions on the mortality of the regions for males and females respectively. In both cases the reference level smooth function for Ireland reflects the expected mortality pattern by age - relatively high mortality at younger ages before falling to the lowest level at around age 10, mortality rises sharply in the late teens followed by a slow increase until middle age before starting to rise steadily thereafter. An “accident hump” in the late teens and early twenties is also visible for males. The shape of the difference smooth for Northern Ireland is consistent with the pattern of the mortality gap between the regions described above - varying by age with the gap greatest at younger ages. The effect of the difference smooth is small reflecting the fact that the largest differences in mortality between the regions occur at younger ages where mortality rates are low. However, as discussed in section 2.2.3, there are important historical reasons affecting the relative mortality differences between the regions at these ages which should be reflected when modelling the mortality of Ireland and Northern Ireland.

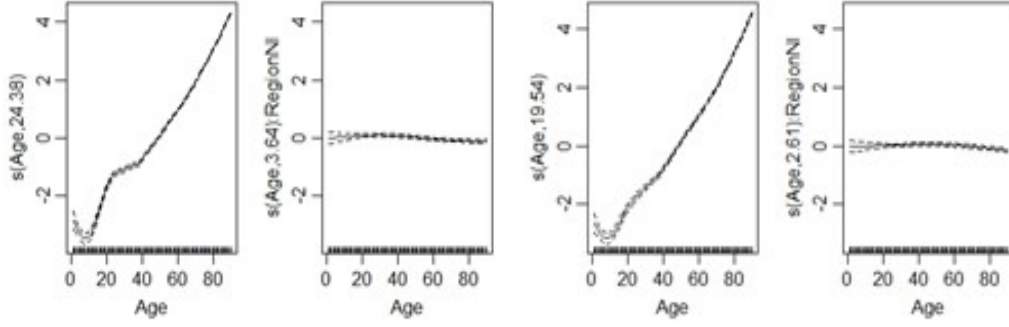


Figure 2.10: Partial effects of smooth functions by region for males and females respectively.

As previously discussed, mortality for Ireland and Northern Ireland tends to converge by approximately age 85 for males and age 90 for females. Given this convergence and the increased volatility of the data at older ages due to low data volumes, it was decided to combine the mortality data for the regions at older ages to provide improved mortality estimates for both regions. The Kannisto model has previously been shown to provide a good fit to Irish mortality data at older ages (Whelan (2009)) and is used in modelling mortality at older ages for the official CSO Population and Labour Force projections for Ireland for 2016-2046 (CSO (2013)) and 2017-2051 (CSO (2018)). The formula for the Kannisto model is as follows:

$$\mu_x = \frac{A * \exp(\beta_x)}{(1 + A * \exp(\beta_x))} \quad (2.5)$$

A Kannisto model was fitted to the combined regional data for ages 80 to 95 for males and females respectively and the models were extrapolated to also provide mortality estimates to age 120. The Kannisto models were implemented using R package “*MortalityLaws*” (version 2.0.3) which provides a choice of methods for fitting the models. The models were fitted using poisson maximum likelihood and separate models were fitted for males and females. Table 2.2 presents the results of fitting the models for the males and females respectively.

	Parameters		Residual Standard Error
	A	B	
Males	0.0495	0.1444	0.0243
Females	0.0336	0.1496	0.0145

Table 2.2: Parameter values for the Kannisto models and goodness of fit results.

The final graduated mortality rates for Ireland and Northern Ireland were obtained by blending the mortality rates from the GAM and the Kannisto models. This was achieved by interpolating between the GAM rates at age 80 and the Kannisto rates at age 85 for males and between the GAM rates at age 85 and the Kannisto rates at age 90 for females. Figure 2.11 presents the final estimates of the mortality rates for Ireland and Northern Ireland for males and females for ages 1 to 120. The resulting mortality rates appear reasonable with a clear gap in mortality between the regions for young adults which reduces with age and no obvious discontinuity in the blending of the mortality rates between the GAMs and Kannisto models. The mortality rates are coherent both within and between the regions - female mortality rates are consistently lower than male mortality rates in each region and mortality rates in Ireland are consistently lower than mortality rates in Northern Ireland for each gender until convergence between the regions is achieved.

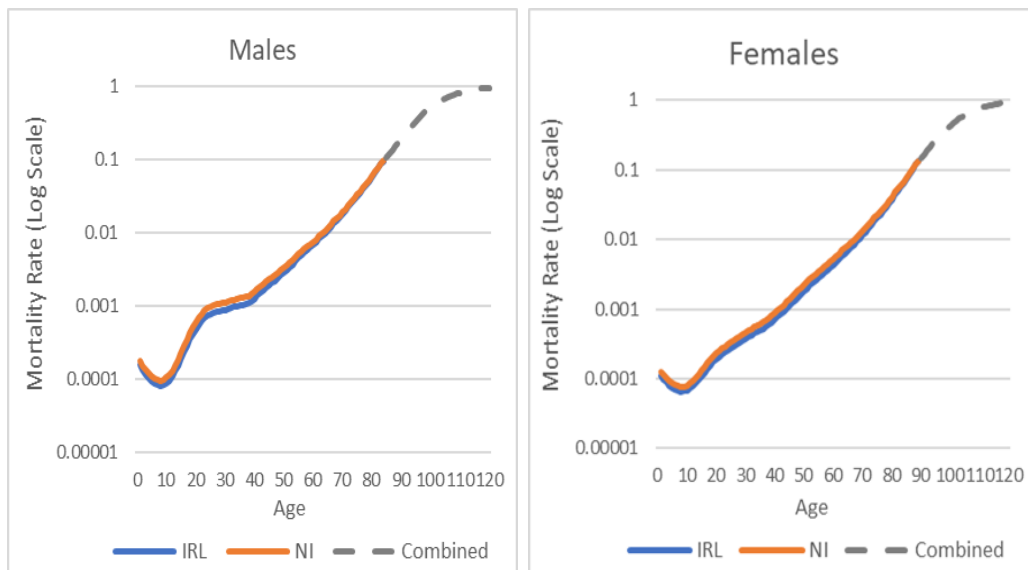


Figure 2.11: Smoothed mortality estimates for Ireland and Northern Ireland for ages 1-120 for males and females respectively.

To create life tables for Ireland and Northern Ireland mortality rates at age 0 were obtained from the EUROSTAT life tables (Eurostat (2023)) by averaging the mortality rates at age 0 for the years 2017-2019 for Ireland and the years 2017 and 2018 for Northern Ireland (no data was available in respect of Northern Ireland for 2019). Life tables were subsequently created for Ireland and Northern Ireland using a starting population (l_0) of 100,000 and extending the life tables until $l_x \geq 0.5$ resulting in a final life table age of 110 for males and 112 for females. For ages > 0 , the life table mortality rates at age x were calculated from the forces of mortality, μ_x , as follows:

$$q_x = 1 - \exp(-\mu_{x+\frac{1}{2}}) \text{ for } x > 0 \quad (2.6)$$

Table 2.3 presents the resulting life expectancies at birth and at age 65 for each region for males and females respectively.

	At Birth		At Age 65	
	Males	Females	Males	Females
Ireland	79.7	83.7	18.6	21.3
Northern Ireland	78.8	82.6	18.4	20.8

Table 2.3: Life Expectancy at Birth & Age 65 for Males and Females in Ireland and Northern Ireland

2.2.5 Impact of Covid-19 on mortality in Ireland and Northern Ireland in 2020 & 2021

The SARS-Cov-2 (Severe Acute Respiratory Syndrome Coronavirus 2), commonly referred to as CoVid-19, pandemic emerged in China in late 2019 and resulted in an estimated 14.9 million excess deaths worldwide in 2020 and 2021 (WHO (2022)). Mortality was highest amongst the elderly and those with underlying health conditions with the impact varying by gender and socio-economic factors as discussed by Bennet et al (2021), Choi (2022), Faramarzi et al (2022) and Wong et al (2023). Research suggests that CoVid-19 should be classified as a syndemic rather than a

pandemic where the impact of CoVid-19 depends both on the disease itself and its interactions with other diseases and social, economic and political factors (Horton (2020), Boes et al. (2021), and Fronteira et al. (2021)).

Figure 2.12 and Figure 2.13 present the trend in the total number of monthly deaths during the pandemic years 2020 and 2021 for males and females combined for Ireland and Northern Ireland respectively. Monthly deaths were obtained from the Central Statistics Office (CSO) for Ireland and from the Northern Ireland Statistics and Research Agency (NISRA) for Northern Ireland. The monthly deaths are based on date of occurrence for Ireland compared to date of registration for Northern Ireland. As a check, we verified that the annual totals of monthly deaths for the regions were equal to the corresponding annual deaths obtained from the Human Mortality Database as discussed in section 2.2.2. Mortality varies throughout the year, being noticeably higher during the winter months, and for comparison, Figures 2.12 and 2.13 also plot the corresponding average monthly deaths for the pre-Covid period (2017-2019). The average monthly deaths were obtained by calculating the average of the deaths for that month across 2017, 2018, and 2019 for each region. Both Ireland and Northern Ireland experienced noticeable peaks in excess deaths during the initial wave of the pandemic in April 2020. Large peaks in excess deaths were also seen in Ireland in January 2021 and in Northern Ireland in the second half of 2021.

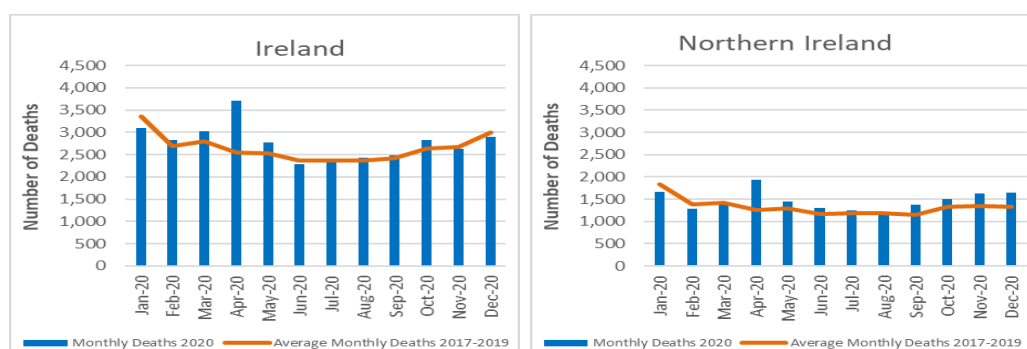


Figure 2.12: Total monthly deaths in 2020 for Ireland and Northern Ireland compared to the corresponding average monthly deaths for the period 2017-2019.

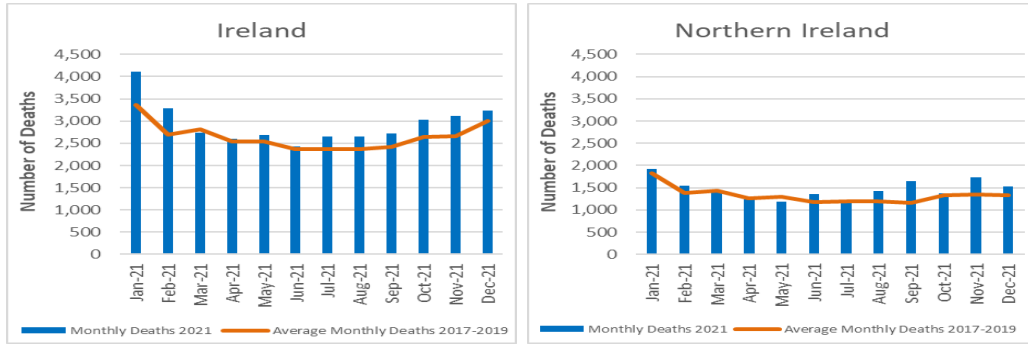


Figure 2.13: Total monthly deaths in 2021 for Ireland and Northern Ireland compared to the corresponding average monthly deaths for the period 2017-2019.

Analysis of all-cause excess mortality is the most common approach for assessing the impact of the Covid-19 pandemic on the mortality of a region and allows assessment of both the direct and indirect effects (e.g. reduced access to healthcare, reduced road traffic accidents) of the pandemic on mortality. We analysed excess mortality by comparing the total number of deaths that occurred during the pandemic with the total deaths which would have been expected to occur if, instead, mortality matched that experienced during the immediate pre-pandemic baseline period 2017-2019. Mortality rates from the life tables of section 2.2.4, which reflect the mortality experience of 2017-2019, were used to calculate the expected deaths in 2020 and 2021 for each region and gender. Table 2.4 presents the resulting excess mortality for Ireland and Northern Ireland during the years 2020 and 2021. The excess deaths are expressed as a percentage of the expected deaths to allow for comparisons between the regions. As can be seen, Northern Ireland experienced higher excess mortality during the pandemic compared with Ireland for both males and females. Noticeably, the analysis demonstrates that Ireland experienced no excess mortality in 2020 and 2021 which is consistent with wider research which indicates that the Covid-19 pandemic had little or no impact on mortality in Ireland (Daly et al. (2024) and Morgan et al. (2023)).

		Actual Deaths		Expected Deaths		Excess Deaths (Actual - Expected)		$\frac{\text{Excess Deaths}}{\text{Expected Deaths}} \times 100$	
		2020	2021	2020	2021	2020	2021	2020	2021
IRL	Male	17,323	18,532	17,990	18,726	-667	-194	-3.7%	1.0%
	Female	16,002	16,716	16,340	16,874	-338	-158	-2.1%	-0.9%
NI	Male	8,733	8,838	8,315	8,511	418	327	5.0%	3.9%
	Female	8,881	8,720	8,321	8,449	560	271	6.7%	3.2%

Table 2.4: Excess mortality during the Covid-19 pandemic years 2020 and 2021 for Ireland (IRL) and Northern Ireland (NI), where the expected deaths were calculated using the 2017–2019 life table mortality rates.

As previously discussed, Ireland experienced exceptional improvements in mortality since the start of the century which, in the absence of the Covid-19 pandemic would have been expected to continue in 2020 and 2021. In an analysis of the effect of the pandemic on life expectancy in 27 countries Huang et al. (2023) show that the impact was more pronounced if year on year intrinsic changes/variations in mortality are considered particularly for countries which experienced greater improvements in life expectancy in recent years. Consequently, we also calculate excess mortality as the difference between the actual deaths and the deaths that would have been expected to occur if the pre-pandemic mortality trends had continued into 2020 and 2021. The pre-pandemic mortality trends for Ireland and Northern Ireland were modelled by fitting the Lee-Carter (Lee (2000), Lee and Carter (1992), and Li and Lee (2005)) model to death data for 2000-2019 and projecting the mortality rates for 2020 and 2021 to obtain the expected deaths in those years.

Projections from the Lee-Carter model can be volatile particularly when projecting by single year of age and for small populations (Basellini, Camarda, and Booth (2023)). Rabbi et al. (2021) discuss various smoothing techniques which have been employed to overcome this limitation and propose the use of LASSO-type regularization to smooth the observed mortality rates prior to fitting the Lee-Carter model. This paper proposes pre-smoothing the observed mortality rates for Ireland and Northern Ireland for the period 2000-2019 using 2-dimensional Generalized Additive Models (2-D GAMs). As before, the GAMs were implemented using R (version 4.2.2) library package “mgcv” (version 1.8-41 (Wood (2001b))). Deaths were assumed to follow a Poisson distribution and the following GAM was fitted to the mortality

data for each region:

$$d_{xy} \sim \text{Poisson}(E_{xy}^c \mu'_{xy}) \quad (2.7)$$

$$\log(\mu'_{xy}) = \beta_0 + f(\text{Age}, \text{Year}) + \log(E_{xy}^c) \quad (2.8)$$

where d_{xy} represents the number of deaths aged x in year y and E_{xy}^c represents the corresponding central exposed to risk. As before, the central exposed to risk was approximated using the mid-year population estimates and μ'_{xy} represents the central mortality rate which approximates the force of mortality, μ , at age $x + \frac{1}{2}$ in year y . f is a 2-dimensional smooth function by age and year implemented using thin plate regression splines. The GAMs were fitted to data for ages 0-95 for years 2000-2019 and separate models were implemented for males and females respectively in each region. Table 2.5 presents the resulting fitted 2-D GAMs. The degrees of freedom for the smooth function in each model were set at 500 (via the parameter “k”) and, as before, the appropriateness of the chosen degrees of freedom was checked by repeatedly refitting the models with “k” set to 750 and 1,000. In each case, there was minimal impact on the resulting effective degrees of freedom of the smooth functions by increasing the degrees of freedom specified.

		β_0	Effective Degrees of Freedom for the 2-D Smooth Functions	R^2 Adjusted
Males	Ireland	-5.4714	416	99.4%
	Northern Ireland	-5.4125	338	98.9%
Females	Ireland	-6.0128	385	99.6%
	Northern Ireland	-5.9440	344	99.3%

Table 2.5: Results of fitting the 2-D GAMs to ages 0-95 for years 2000-2019 for smoothing the mortality trends for Ireland and Northern Ireland prior to fitting the Lee-Carter model.

The Lee-Carter model was fitted to the resulting smoothed mortality data for 2000-2019 and mortality rates projected for 2020 and 2021. The Lee-Carter model was implemented using R package StMoMo (Villegas, Kaishev, and Millossovich (2018)) which fits the model using poisson maximum likelihood and forecasts were

generated using the default random walk with drift approach. The basic form of the Lee-Carter model has three parameters: α_x represents age-specific mortality levels, β_x represents the sensitivity of mortality at each age to changes in the time index, and κ_t is the time index capturing the overall level of mortality over time (Lee and Carter (1992)). Figures 2.14 and 2.15 show the parameter values for the fitted Lee-Carter models for males and females in Ireland and Northern Ireland. While the shape of the graphs between Ireland and Northern Ireland are broadly similar, the slope of the time index graph (κ_t) is much larger for Ireland compared to Northern Ireland confirming Ireland experienced more rapid mortality improvements over the period 2000-2019. Furthermore, in contrast to Northern Ireland, males and females in Ireland show very similar projected values for parameter κ_t in 2020 and 2021.

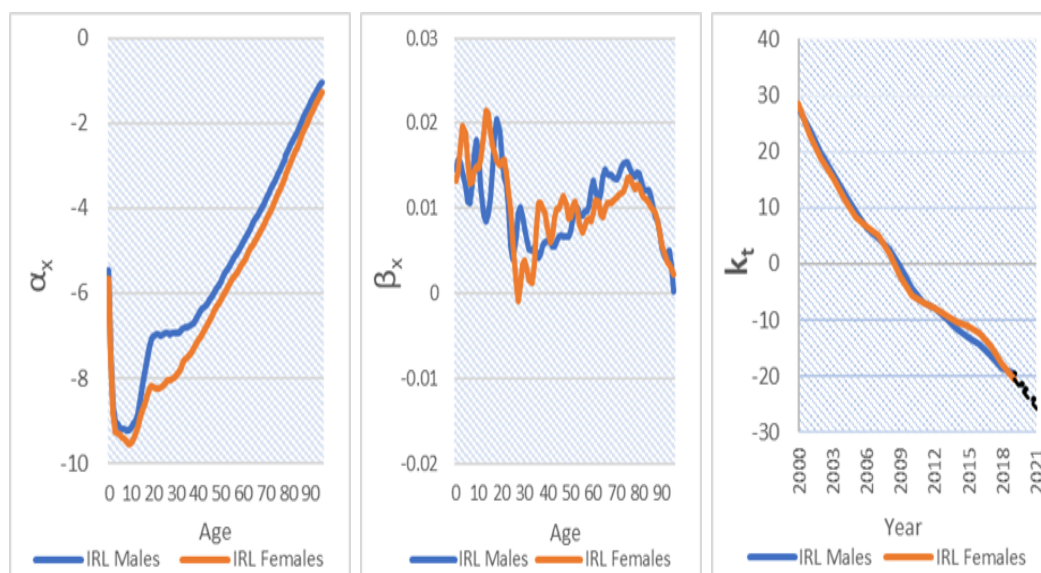


Figure 2.14: Parameter values from the Lee-Carter models fitted to the pre-smoothed mortality rates for the period 2000-2019 for males and females in Ireland (IRL) including the projected κ_t values for 2020 and 2021.

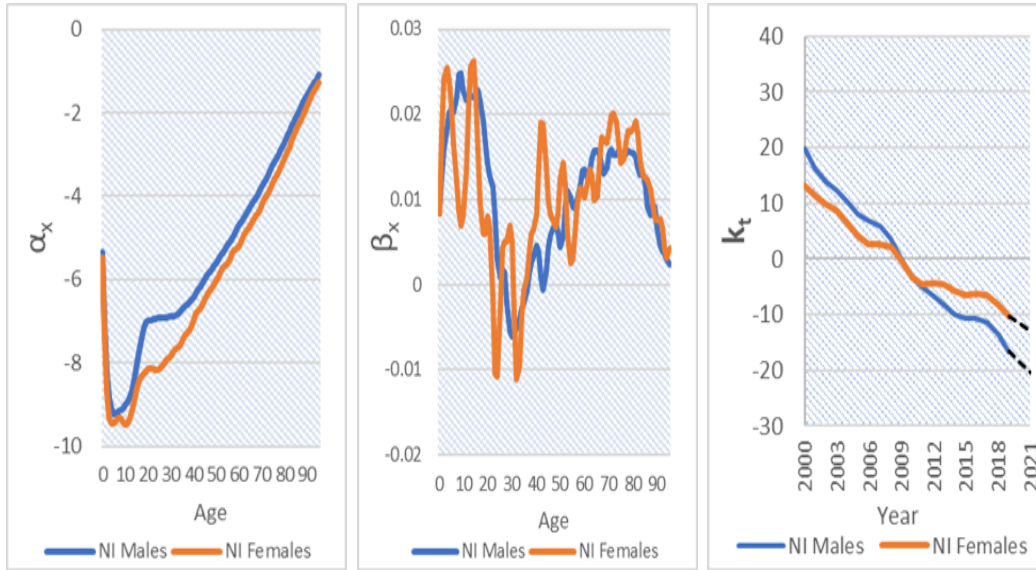


Figure 2.15: Parameter values from the Lee-Carter models fitted to the pre-smoothed mortality rates for the period 2000-2019 for males and females in Northern Ireland (NI) including the projected κ_t values for 2020 and 2021.

Applying the same approach as in section 2.2.4, mortality rates at older ages were obtained by fitting the Kannisto model to the projected rates in 2020 and 2021 for ages 80-95 for each region and gender separately and extrapolating to age 120. Subsequently, life tables for 2020 and 2021 were obtained by blending the mortality rates from the Lee-Carter and Kannisto models as previously described. Expected deaths, allowing for pre-pandemic trends, were then calculated for each region and Table 2.6 shows the resulting excess deaths for 2020 and 2021. Comparing with the results in Table 2.4, it can be seen that the number of excess deaths in each region increases when we allow for the projection of the pre-pandemic mortality trends. In particular, Ireland now records overall excess deaths in both pandemic years though the excess deaths as a percentage of expected deaths still remains lower than that for Northern Ireland. Under both approaches for calculating excess mortality, the pandemic is generally shown to have had a more severe overall impact on the mortality of Northern Ireland relative to Ireland.

		Actual Deaths		Expected Deaths		Excess Deaths (Actual - Expected)		$\frac{\text{Excess Deaths}}{\text{Expected Deaths}} \times 100$	
		2020	2021	2020	2021	2020	2021	2020	2021
IRL	Male	17,323	18,532	17,250	17,477	73	1,055	0.4%	6.0%
	Female	16,002	16,716	15,571	15,726	431	990	2.8%	6.3%
NI	Male	8,733	8,838	7,818	7,831	915	1,007	11.7%	12.9%
	Female	8,881	8,720	8,060	8,072	821	648	10.2%	8.0%

Table 2.6: Excess mortality during the Covid-19 pandemic years 2020 and 2021 for Ireland (IRL) and Northern Ireland (NI), where the expected deaths are based on mortality projections from the Lee-Carter model applied to pre-smoothed mortality rates for 2000-2019.

2.2.6 Discussion/Conclusion

Ireland experienced significant improvements in mortality in the early decades of the 21st century. The economy of a country influences its mortality through spending on healthcare and general living conditions and since the 1990s the Irish economy has experienced rapid economic growth (albeit with fluctuations). As discussed by O’Gráda and O’Rourke (2022) Ireland transitioned from “one of the poorer countries in Europe” in the 1980s to one of the richest economies in the world in 2021. Healthcare expenditure correspondingly rose with real public health spending per capita in Ireland increasing by 800% over the 25 years to 2019 (Casey and Carroll (2021)). In contrast, mortality in Northern Ireland generally disimproved relative to Ireland over the course of the 21st century. By 2019, immediately prior to the CoVid-19 pandemic, Northern Ireland experienced higher relative mortality except for the very oldest age group where mortality between the regions had effectively converged. While the reasons for the current higher mortality Northern Ireland are not fully understood research indicates that Northern Ireland experiences high rates of chronic diseases and long-term health related limitations relative to both the Republic of Ireland and Britain (McDaid et al. (2013), Sheehan and O’Sullivan (2020), and Baraniuk (2021)). In general, mortality improvements in both regions were higher in the first decade of the century relative to the second decade. The lower improvements witnessed in the second decade of the 21st century (2010-2019) are consistent with international trends. Research indicates that post 2010 and prior

to the emergence of Covid-19 many countries experienced a slowdown in mortality improvements. The effects of austerity post the Great Recession of 2008-2009 and noticeably higher winter mortality in certain years are the main reasons proposed for this stalling of mortality improvements (Public Health England (2018), Continuous Mortality Investigation (2020), Jones (2020), and Djeundje et al. (2022)).

Jointly modelling the mortality rates for Ireland and Northern Ireland produces more coherent mortality estimates for the regions which benefit from borrowing strength across the populations. We have presented a simple method for jointly modelling Irish and Northern Irish mortality rates across the majority of the age range using Generalized Additive Models. The relatively small size of the population for Northern Ireland increases the volatility of the crude mortality rates for the region. In particular, for the three-year period, 2017-2019, zero deaths were recorded at age 9 for females in Northern Ireland and separately modelling the mortality of the regions using GAMs resulted in an unrealistic mortality pattern for Northern Irish females at younger ages. The use of a difference model to model the mortality of Northern Ireland relative to Ireland recognises the relative difference in population size between the regions and can improve the credibility of mortality estimates where a consistent mortality pattern between the regions exists. At older ages, we exploited the convergence of the mortality rates between the regions by modelling aggregated regional mortality data using a Kannisto model, which allows for extrapolation to high ages. The resulting life tables provide smooth, coherent, region-specific mortality rates which extend well beyond the age range of the current, national life tables for the regions and provide a more appropriate basis for mortality assumptions for actuarial applications, particularly for aging populations.

Small populations can experience relatively volatile mortality rates and, consequently, can benefit from using smoothed mortality rates to estimate expected deaths when calculating excess mortality. Therefore, the 2017-2019 life tables were subsequently used to calculate expected deaths in 2020 and 20201 to provide improved estimates of excess mortality for the regions during the Covid-19 pandemic.

Furthermore, in the absence of the pandemic the mortality improvement trends of the first two decades of the 21st century would have been expected to continue into 2020 and 2021 and excess mortality for the regions was also calculated based on projected mortality rates for 2020 and 2021. The projected mortality rates were obtained by fitting the Lee-Carter model to the pre-pandemic period 2000-2019. Again, to allow for the relatively small size of the populations and the resulting mortality volatility the mortality rates for 2000-2019 were pre-smoothed using 2-dimensional GAMs. Compared to directly fitting the Lee-Carter to the mortality of the regions this simple method for pre-smoothing the mortality rates resulted in more reasonable overall mortality projections for 2020 and 2021 and hence improved excess mortality estimates.

The impact of the Covid-19 pandemic varied between the regions reflecting differences in public health restrictions between the regions in response to the pandemic (lockdowns, social distancing, work from home advice, school and college closures, closure of non-essential services etc). Overall, however, Ireland experienced lower excess mortality relative to Northern Ireland during the pandemic years 2020 and 2021. This is consistent with a report by the Health Information and Quality Authority (HIQA) which noted that Irish government policies to reduce the transmission of the virus as measured using the Oxford Stringency Index (Mathieu et al. (2020)) between March 2020 and May 2021 (i.e. prior to widespread high vaccination rates for the over 70s) were regularly among the most stringent in Europe (Health Information and Quality Authority (2022)). Similarly, Cazelles et al (2021) modelled the transmission of the Covid-19 virus in Ireland and concluded that Ireland significantly reduced transmission of the virus during the main waves of the pandemic in 2020 and early 2021 through a variety of mitigation measures, physical distancing and lockdowns and thereby “avoided the saturation of healthcare infrastructure . . . and likely reduced mortality”. While the future impact of Covid-19 on mortality is uncertain analysis from other European countries, suggests, that in line with past mortality shocks (such as the 1918 Influenza pandemic) mortality is expected to

return to, or close to, pre-pandemic levels in the coming years (Huang et al. (2023), Office for National Statistics (2022), and CBS Netherlands (2022)).

In summary, in the absence of industry specific life tables, jointly modelling the mortality of Ireland and Northern Ireland can provide improved region-specific mortality estimates which are more appropriate for actuarial applications. The improved mortality estimates would also be of benefit to wider, demographic applications and can help identify significant mortality disparities between the regions which may benefit from targeted government interventions.

Appendix: Comparison of Recent Pre-Pandemic Official Life Tables for Ireland and Northern Ireland

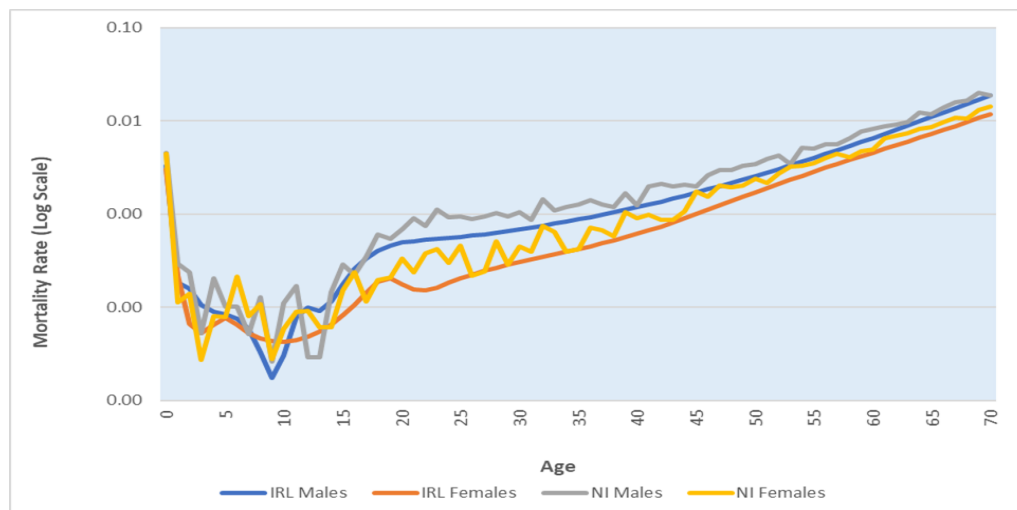


Figure 2.16: Mortality rates for ages 0-70 from Irish Life Table 17 for Ireland (IRL) covering the period 2015-2017 and the National Life Table for 2015-2019 for Northern Ireland (NI).

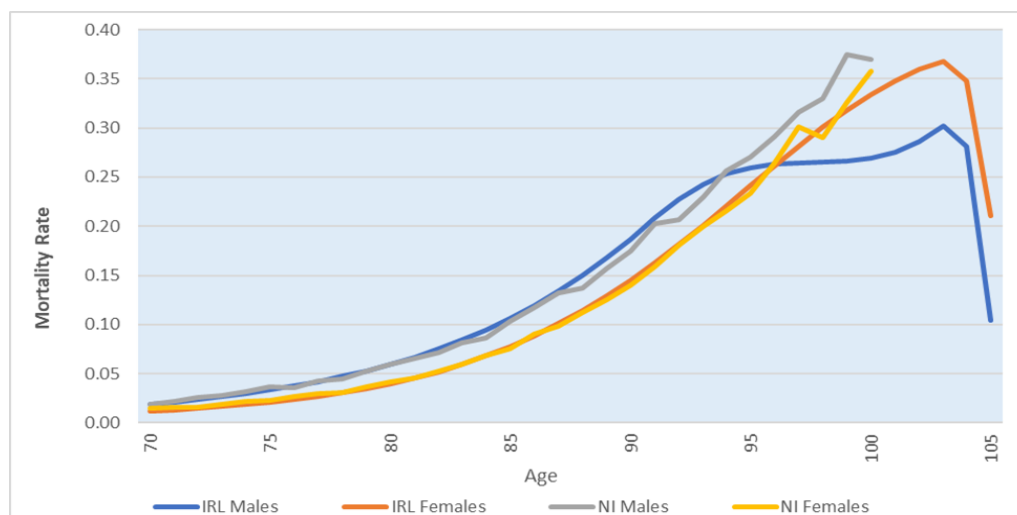


Figure 2.17: Mortality rates for ages 70+ from Irish Life Table 17 for Ireland (IRL) covering the period 2015-2017 and the National Life Table for 2017-2019 for Northern Ireland (NI).

Appendix 2: Implications of the New Life Tables in Ireland and Northern Ireland

Cross-subsidies in pension pricing are increasingly viewed as unacceptable, particularly in the context of increasing regulatory requirements and consumer fairness standards. With improved access to granular demographic data and advances in actuarial modelling techniques, there is an increasing need to refine pricing models to more accurately reflect individual risk characteristics.

As shown in Figure 2.11, the newly developed life tables for Ireland and Northern Ireland present smooth, consistent and region-specific mortality rates. These tables extend significantly beyond the age range covered by the existing life tables, offering a more stable and appropriate basis for setting mortality assumptions in actuarial applications. Figures 2.18 and 2.19 compare the existing national life tables with the new graduated tables for both Ireland and Northern Ireland. As is evident, the new tables exhibit significantly reduced volatility and extend well beyond the age limits of the existing tables—an increasingly important feature in the context of an ageing population such as Ireland and Northern Ireland.

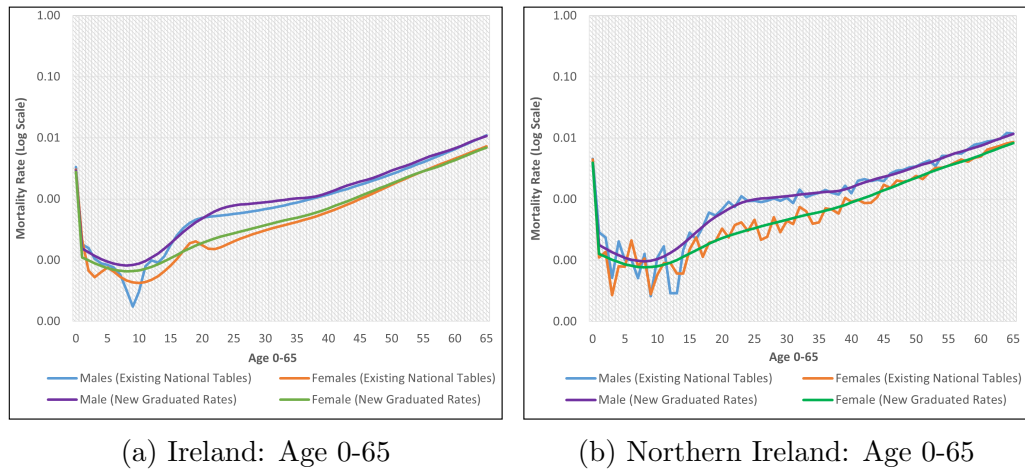
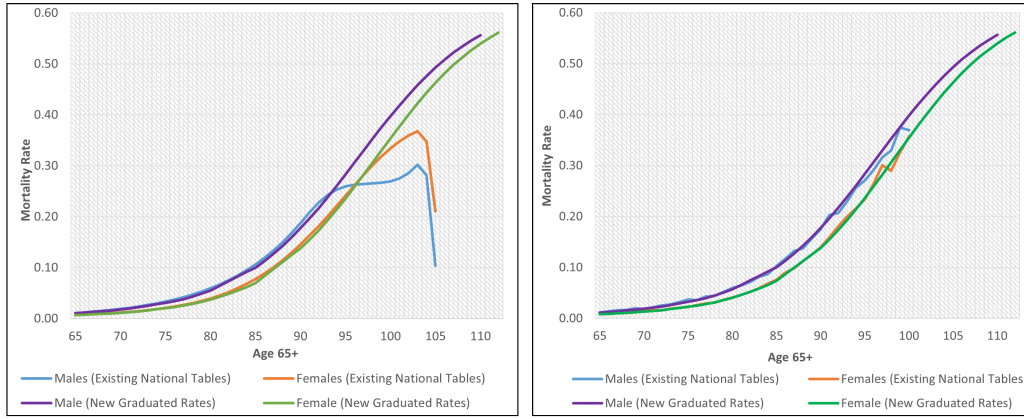


Figure 2.18: Comparison of existing life tables for Ireland (ILT17) and Northern Ireland (National Life Table 2015-2017) with the new graduated tables for ages 0-65



(a) Ireland: Age 65+

(b) Northern Ireland: Age 65+

Figure 2.19: Comparison of existing life tables for Ireland (ILT17) and Northern Ireland (National Life Table 2015-2017) with the new graduated tables for ages 65+

From an actuarial perspective, the financial implications of these updated tables are important. Table 2.7 presents annuity values for males and females retiring at age 65 based on both the new and existing life tables, assuming a fixed interest rate of 3% per annum. To ensure comparability, annuity values were calculated using a maximum age of 100 for Northern Ireland and 105 for Ireland, aligning with the upper age limits of the respective existing life tables.

	Male ROI	Female ROI	Male NI	Female NI
	$\ddot{a}_{65:\overline{40} }$	$\ddot{a}_{65:\overline{40} }$	$\ddot{a}_{65:\overline{35} }$	$\ddot{a}_{65:\overline{35} }$
Existing Table	14.05	15.58	13.96	15.32
New Table	14.27	15.77	14.11	15.43
% Difference	1.5%	1.2%	1.1%	0.7%

Table 2.7: Comparison of annuity rates at age 65, assuming a fixed 3% p.a. interest rate, between the periods 2015–2017(Existing Table) and 2017–2019 (New Table). The Existing Life Table is titled ILT17 for Ireland National Life Table 2015-2017 for Northern Ireland.

The results show an increase in the cost of providing pensions in both regions, with a more pronounced rise observed in Ireland. Specifically, annuity rates have increased between 0.7% and 1.5%, depending on gender and region. While these increases changes may appear relatively modest, even small increases in annuity rates can materially affect the funding requirements of private occupational pension schemes particularly those with large member populations. In the public sector, the

upward revision in life expectancy assumptions may lead to budgetary pressures, particularly in the context of long-term pension sustainability.

Beyond actuarial practice, these refined mortality estimates have important implications for broader demographic and public policy analysis. By revealing systematic differences in mortality trends between Ireland and Northern Ireland, the models can help identify underlying socioeconomic, healthcare, or environmental factors contributing to these disparities. This, in turn, can support the development of more targeted and effective government interventions aimed at improving population health outcomes and reducing regional inequalities in life expectancy.

Finally, beyond the implications of the revised life tables for both Ireland and Northern Ireland, the substantial mortality improvements recorded between 2000 and 2017 have considerably increased the cost of providing pensions. Table 2.8 compares annuity factors at age 65 for the periods 2001–2003 and 2017–2019, using the official life tables applicable to each region in 2001–2003, together with the newly graduated rates for 2017–2019 as outlined earlier. The results show a significant rise in pension costs in both regions, with the increase being particularly pronounced in Ireland.

	Male ROI	Female ROI	Male NI	Female NI
	$\ddot{a}_{65:\overline{40} }$	$\ddot{a}_{65:\overline{40} }$	$\ddot{a}_{65:\overline{35} }$	$\ddot{a}_{65:\overline{35} }$
2001-2003	12.29	14.20	12.56	14.38
New Table	14.27	15.77	14.11	15.43
% Difference	16.1%	11.1%	12.3%	7.3%

Table 2.8: Comparison of annuity rates at age 65, assuming a fixed 3% p.a. interest rate, between the periods 2001–2003 and 2017–2019 (New Table). The 2001–2003 table is titled ILT14 for Ireland and National Life Table 2001–2003 for Northern Ireland.

2.3 Additional Mortality Trend Measures between Ireland & Northern Ireland

2.3.1 Mortality by Cause of Death 2017-2019

Mortality varies by cause of death and geographical variations by cause of death can assist in understanding differences in disease prevalence and mortality between regions. Northern Ireland has classified deaths by cause using the World Health Organisation (WHO) International Classification of Diseases revision 10 (ICD-10) since 2001. Ireland, however, did not move to ICD-10 until 2007. Consequently, trends in mortality by cause of death were not analysed for Ireland and Northern Ireland. Instead, mortality by cause of death was only investigated for the most recent (pre-Covid) period by averaging deaths over the three years 2017-2019.

The Central Statistics Office (CSO) provided data on deaths in Ireland by cause of death over the period 2017-2019 and were grouped in 5-year age bands up to age 84, with a combined category for ages 85 and over (CSO (2021)). The CSO also supplied population estimates over the same period by gender (effective 01st April), which are assumed to approximate mid-year estimates (CSO (2024d)). Comparable death data for Northern Ireland were provided by the Northern Ireland Statistics and Research Agency (NISRA). Population estimates for Northern Ireland were sourced from the Human Mortality Database (HMD), as described in section 2.2.2. These population estimates, effective 01st January were averaged across consecutive years to derive mid-year population estimates by gender for the period 2017–2019.

Figure 2.18 presents the proportion of deaths for the five main causes of death for all ages combined over the period 2017-2019 for males and females respectively in Ireland and Northern Ireland. With the exception of males in Ireland the five main causes of death are: Neoplasms (C00-D48), Circulatory Diseases (I00-I99), Respiratory Diseases (J00-J99), Dementia and Alzheimer’s (F00-F03, G30) and all Other causes combined. For males in Ireland external causes of injury and poisoning

(including intentional self-harm)(V00-Y98) is the 5th leading cause of death replacing Dementia and Alzheimer's. Neoplasms was the primary cause of death across both genders and regions followed by Circulatory Diseases.

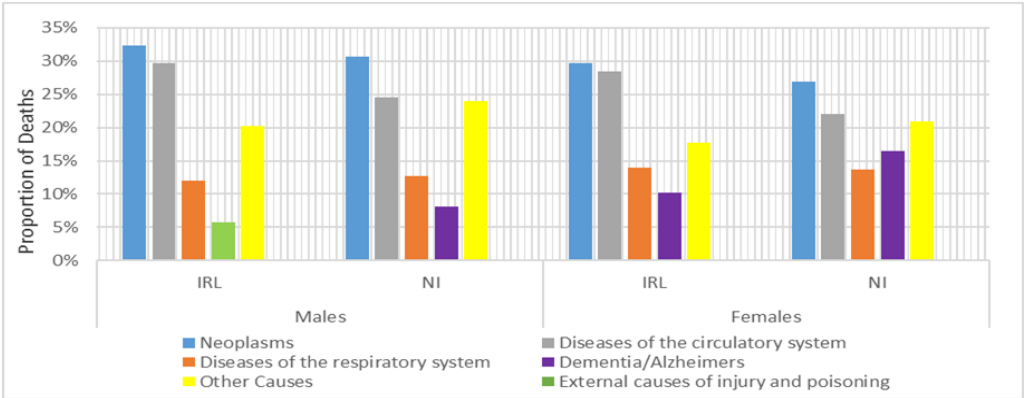


Figure 2.20: Proportion of deaths in Ireland (IRL) and Northern Ireland (NI) for all ages by major cause of death for males and females over the 3-year period 2017-2019.

Figure 2.19 presents the corresponding ASMR for each of the main causes of death. The ASMR by cause of death was calculated based on deaths by 5-year age group up to age 84 and for ages 85+ combined. Dementia/Alzheimer's show the largest gap between Ireland and Northern Ireland for males and females with a 71% higher mortality rate for males and 75% higher rate for females. Additionally, for both Northern Ireland and Ireland, Dementia/Alzheimer's is the only cause of death where the mortality rate is higher for females compared to males.

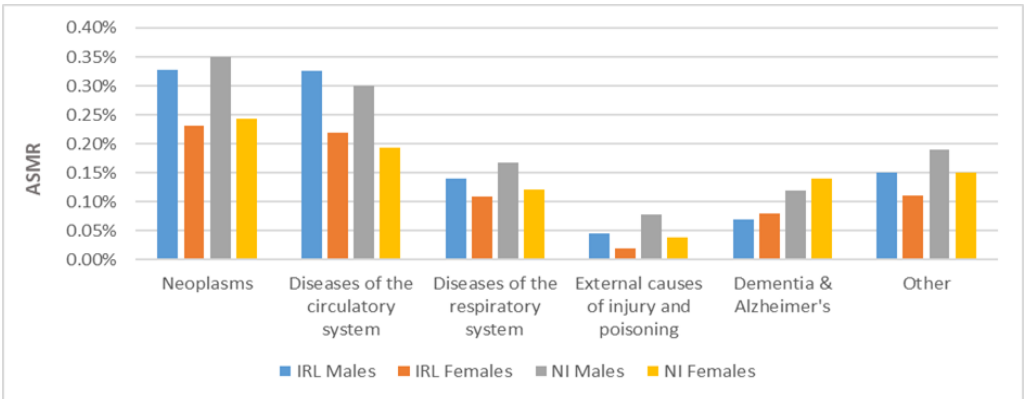


Figure 2.21: ASMR in Ireland (IRL) and Northern Ireland (NI) by major cause of death for males and females over the 3-year period 2017-2019.

The proportion of deaths by cause varies by age group. Figure 2.20 presents the proportion of deaths for the five main causes of death for age groups 0-59, 60-79 and 80+ for the period 2017-2019 for males and females respectively in each region. The main causes of death were consistent between the regions within each age group and gender combination. Neoplasms was the primary cause of death for age groups 0-59 and 60-79, with the exception of males in Northern Ireland in the youngest age group, for whom the primary cause of death was external causes of injury and poisoning. In particular, Neoplasms accounted for almost 50% of all female deaths in age group 0-59 in Ireland. For the oldest age group, 80+, circulatory diseases constituted the primary cause of death.

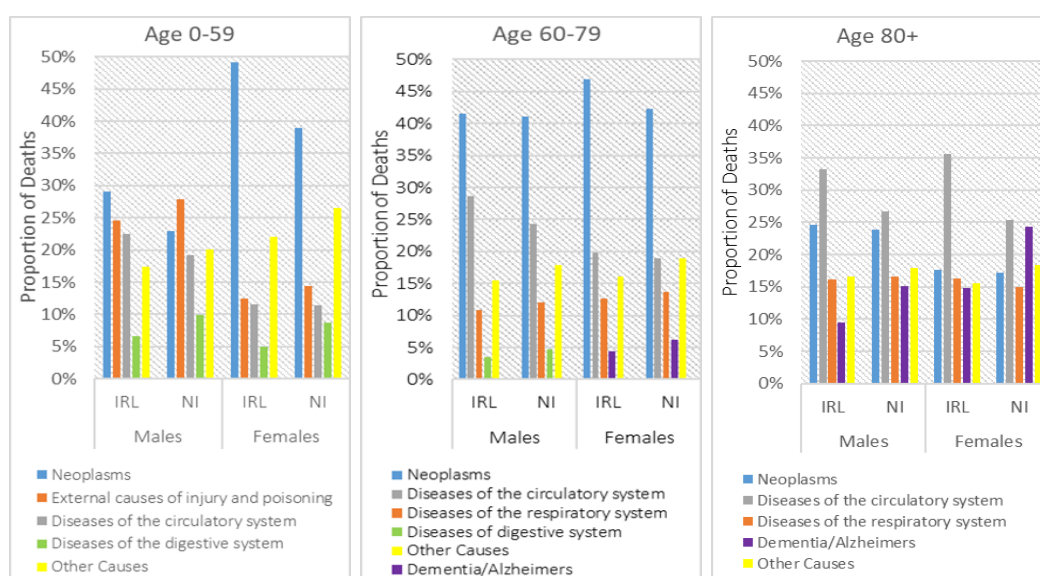


Figure 2.22: Proportion of deaths in Ireland (IRL) and Northern Ireland (NI) by major cause of death and age group over the 3-year period 2017-2019 for males and females.

2.3.2 Premature Mortality

Crude and specific measure of mortality describe the death rates in a population but they fail to quantify the burden of loss resulting from premature mortality. The concept of Years of Potential Life Lost (YPLL) involves estimating the average time a person would have lived had he or she not died prematurely. This measure is used to help quantify social and economic loss owing to premature death (Gardner and

Sanborn (1990)). YPLL is based on the assumption that that the younger a person dies the greater the loss of life and therefore the calculation of YPLL weights those who die at the younger ages heavier than those who die at later ages. To calculate the years of potential life lost, an arbitrary upper reference called the standard age must be chosen. The YPLL calculation does not include people who died at the standard age or older and the most common method is to calculate a YPLL rate per 1,000 (or 10,000 or 100,000) population known as the Years of Potential Life Lost Index (YPLLI).

The calculation of the YPLL is as follows:

$$\sum_{i=l}^L (L - i) * d_i \quad (2.9)$$

where: l =lower age limited established,

L =upper age limited established,

i = age of death

d_i = number of deaths at age i

The calculation of the YPLLI is based on the following formula:

$$\frac{YPLL}{N} * 1,000 \quad (2.10)$$

where: N is the population between the lower and upper age limits

For this analysis, a lower age limit of 0 and an upper age limit of 65 was assumed and the data used was the same as described in section 2.2.2. Table 2.7 shows the YPLLI (per 1,000 population) for the 3-year period 2017-2019 (averaged), 2020 and 2021 for both Ireland and Northern Ireland for males and females.

As can be seen the YPLLI is significantly higher in Northern Ireland compared to Ireland for both males and females. The YPLLI in Northern Ireland has been increasing steadily from 2017-2021.

	Ireland		Northern Ireland	
Year	Male	Female	Male	Female
2017-2019	28.8	18.0	35.4	21.6
2020	27.7	17.1	36.4	21.8
2021	28.1	17.2	38.0	23.6

Table 2.9: The YPLLI for males and females in Ireland & Northern Ireland for 2017-2019 (averaged), 2020 and 2021

2.3.3 European Comparison

The impact of the pandemic varied widely across Europe reflecting differences in the timings of the arrival of the Covid-19 virus in each country and subsequent government strategies for mitigating the impact of the virus. For context, this section compares the impact of the pandemic in Ireland and Northern Ireland with a range of other European countries. Death and population data for all countries was obtained from the Human Mortality database as of 06 February 2025 (HMD (2025)). Deaths and population estimates were obtained by single year of age and gender for the years 2017 to 2022. The population estimates were effective on the 1st January and mid-year population estimates by gender for ages 0-99 for the years 2017 - 2021 were obtained by averaging the HMD population estimates across consecutive years.

The comparison considered the change in the ASDR for a selection of European countries in 2020 and 2021 relative to the average ASDR for the pre-pandemic period 2017-2019. The change in the ASDR for each country was calculated as follows:

$$1 - \frac{ASDR_{XYZ}}{\text{Average } ASDR_{XYZ} \text{ for 2017-2019}} \quad (2.11)$$

where x represents the age range (0-99), y represents the year (2020 or 2021) and z represents the country. A positive value represents an improvement or a drop in mortality relative to the 2017-2019 average while a negative value represents a disimprovement or a rise in mortality.

Figures 2.21 presents the changes in ASDR rates for the age group 0-99 across 13 European countries (including both Ireland and Northern Ireland) for the years 2020

and 2021. In 2020, Ireland exhibited a mortality improvement for males and females compared to Northern Ireland which experienced a significant dis-improvement. The majority of the other European countries in the analysis experienced a dis-improvement in 2020 for males and females, with the exception of Denmark and Norway which like Ireland witnessed an improvement. Belgium, Italy, and Spain exhibited the most significant mortality dis-improvements while Norway experienced the most substantial mortality improvement. The rates of change in mortality rates in 2021, compared to the average mortality rates from 2017 to 2019, were less pronounced than that experienced in 2020. Out of the 13 countries considered, 6 showed improvements in 2021 including Ireland, Belgium, Denmark, Norway, Sweden and Switzerland. Norway and Sweden experienced the most substantial improvements in 2021 whereas Italy, the Netherlands, and Portugal witnessed the biggest deterioration. Similar to 2020, Northern Ireland experienced a decline in 2021, although the magnitude of the decline was significantly smaller than what was experienced in 2020. Finally among the 13 countries analysed, 7 countries (France, Italy, Netherlands, Portugal, Spain (males only) Northern Ireland, and England & Wales) experienced a consecutive dis-improvement in mortality for 2020 and 2021 whereas 3 countries (Denmark, Ireland and Norway) experienced consecutive improvements.

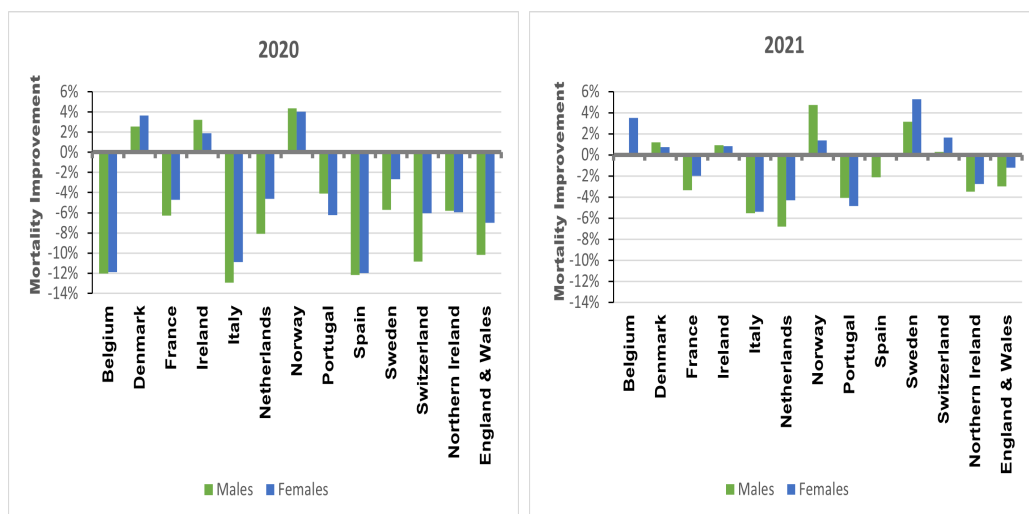


Figure 2.23: Changes in the ASDR rates for 2020 and 2021 compared to the average ASDR in 2017-2019, for 13 European counties, over the age range 0-99 for males and females respectively.

Chapter 3

Seasonal Mortality at Older Ages in Ireland

3.1 Introduction

Mortality varies by season with the seasonal differences in mortality increasing with increasing age. Seasonality of mortality is a source of demographic basis risk and trend risk for insurers and pension providers contributing to their overall mortality and longevity risk (Hall and Naqvi (2023)) in the winter with the increase mainly attributable to cold (poor) housing and influenza (Fowler et al. (2015)). While the magnitude of seasonal differences in mortality has declined in recent decades across Europe factors such as the increased likelihood of extreme temperatures due to climate change and the emergence of SARS-CoV-2 in 2019 have the potential to directly increase the variability of seasonal mortality differences over both the short and the long term (Murtas and Russo (2019), Hajat (2017), Ballester et al. (2011), and Liu et al. (2021)). Management of mortality and longevity risk benefits from understanding the impact of seasonality on annual mortality trends.

Despite its relatively mild winters, Ireland experiences significant seasonal variations in mortality among older age groups compared to its European counterparts (Clinch and Healy (2000)). As one of the fastest-aging member states in the EU

(Commission (2024)), understanding the impact of seasonality on mortality in Ireland is becoming increasingly important. The proportion of the population aged 65+ is projected to rise to between 28% and 32% of the total population by 2057, depending on migration trends (CSO (2024b) and CSO (2024c)). Furthermore, people are living longer, between 1990 and 2018 the life expectancy for both males and females in Ireland increased significantly, from 74.8 to 82.1 years (HMD (2024)). Seasonal variations in mortality contribute to the uncertainty surrounding future mortality projections, highlighting the growing need to better understand these trends as the population continues to age.

Ireland experienced significant improvements in mortality at older ages during the period commonly referred to as the ‘Celtic Tiger’ from approximately the mid 1990s to 2007 when the Irish economy underwent an unprecedented boom (achieving an average GDP growth of 6.5% per annum (Macrotrends (2024))). In the 30 years preceding the Celtic Tiger, Ireland’s health expenditure was considerably below the EU average, particularly for capital expenditure, amounting to just 66% of the EU average over the period 1970–1996 (Wren (2004)). Health expenditure soared during the Celtic Tiger era increasing to 7.7% of GDP in 2007 (Statista (2024), Appendix 3). The “Celtic Tiger” was followed by the global financial crisis of 2008/2009 which had a severe impact on the Irish economy. Ireland entered recession in 2008 and was forced to accept an EU/IMF bailout in November 2010 (European Commission (2019)). Successive budgets implemented measures to reduce public expenditure, including cuts to health spending. For instance, the total public health budget decreased from €15.4 billion in 2008 to €13.9 billion in 2012 (Thomas et al. (2012), Nolan et al. (2014), and Department of Public Expenditure and Reform (2012)).

Ireland began to recover from the recession in 2012 and by 2014, recorded a GDP growth rate of 8.6% (Macrotrends (2024)). This growth was significantly bolstered by substantial foreign direct investment, particularly in the technology sector, leading to the development of Dublin’s ‘Silicon Docks’ where major technology companies like Google and Facebook established their European headquarters (Silicon

Docklands (2025) and Wikipedia (2025)).

Figure 3.1 presents the annual mortality improvements attained pre the Celtic tiger era (1988-1997), during the Celtic Tiger era (1998-2007) and post the Celtic Tiger era (2008-2017) in Ireland for ages 60-90 for males and females respectively. As shown in Figure 3.1, mortality improvements were most pronounced during the Celtic Tiger era for both males and females. Since this age group are the most impacted by seasonal variations in mortality, analysing how these improvements differed by season can enhance our understanding of the factors influencing mortality trends in older populations.

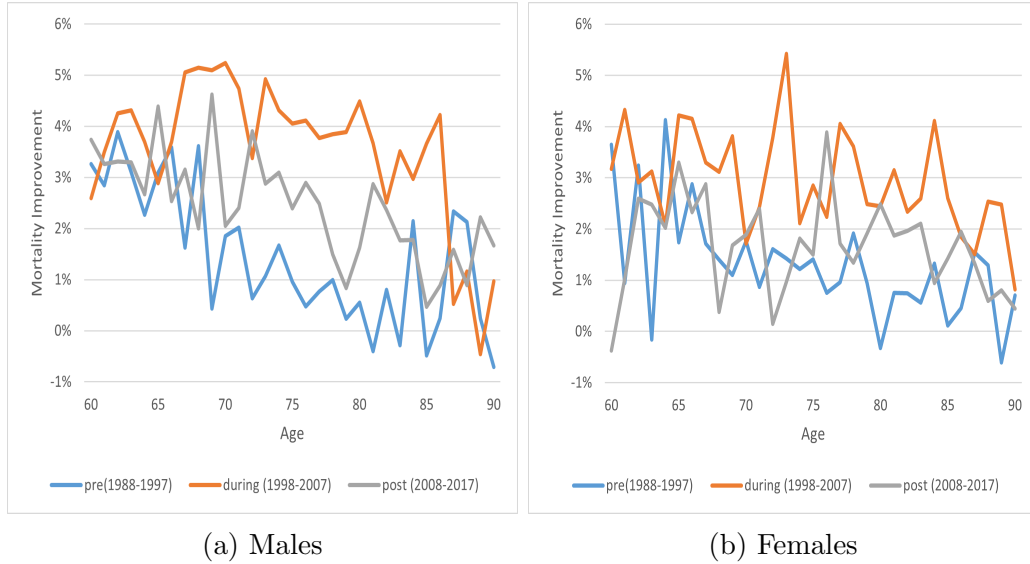


Figure 3.1: Annual Mortality Improvements for the 10 years pre, during and post the Celtic Tiger for ages 60–90 for males and females respectively.

In Europe seasonal differences in mortality vary between the countries. The reasons for seasonal differences in mortality across Europe are complex and their impact varies over time but research suggests differences in housing standards, macroeconomic factors, and public health action as contributing factors (Clinch and Healy (2000), Healy (2003), and Fowler et al. (2015)). Multipopulation models are becoming increasingly common in modelling and projecting mortality rates (Haberman et al. (2014)). Factors affecting mortality such as lifestyle improvements, medical advances and public health policy exert a similar influence on related populations. By jointly modelling the mortality of two or more related populations or sub popu-

lations multipopulation models aim to improve the consistency and accuracy of the mortality forecasts for each (sub) population. Multipopulation models typically assume that the spread or the relative difference in mortality between the population forecasts will tend to the mean historical differences between the populations (Li and Lee (2005) and Cairns et al. (2011b)). At older ages changing seasonal trends between populations may, potentially, invalidate such assumptions, increasing the risk associated with future projections. Furthermore, climate change may be expected to influence regional disparities in seasonal mortality.

This chapter provides a detailed analysis of seasonal mortality among older ages in Ireland and is structured as follows:

- **Section 3.2** – Describes the data used in the analysis.
- **Section 3.3** – Details the methodology used in the analysis.
- **Section 3.4** – Analyses seasonal mortality trends for males and females aged 60-90 in Ireland between 1986 and 2017.
- **Section 3.5** – Analyses future forecasts of non-winter mortality rates and conducts sensitivity tests for winter mortality
- **Section 3.6** – Examines the impact of different institutional living arrangements on seasonal mortality variations in the elderly from 2013 to 2017.
- **Section 3.7** – Explores the relationship between marital status and excess winter mortality.
- **Section 3.8** – Discusses the results and provides overall conclusions.

3.2 Data

To analyse the seasonal mortality trends in Ireland data on the number of deaths by age, gender, month and year were obtained from the Central Statistics Office (CSO) Ireland for the period 1986-2018. Given seasonal mortality has the greatest impact at older ages deaths are analysed for ages 60-89 with deaths for those who died at older ages excluded from the analysis due to low data volumes. Deaths are based on date of occurrence of death. Exposure data for the period 1986-2017 was obtained from the Human Mortality Database (HMD (2019)) - the exposure data for 2018 was unavailable at the time of carrying out the analysis. Figure 3.2 presents the increase in the exposure data over the period. The population exposed to the risk of death are based on annual (01st January) population estimates, with small corrections that reflect the timing of deaths during the interval (HMD (2021)).

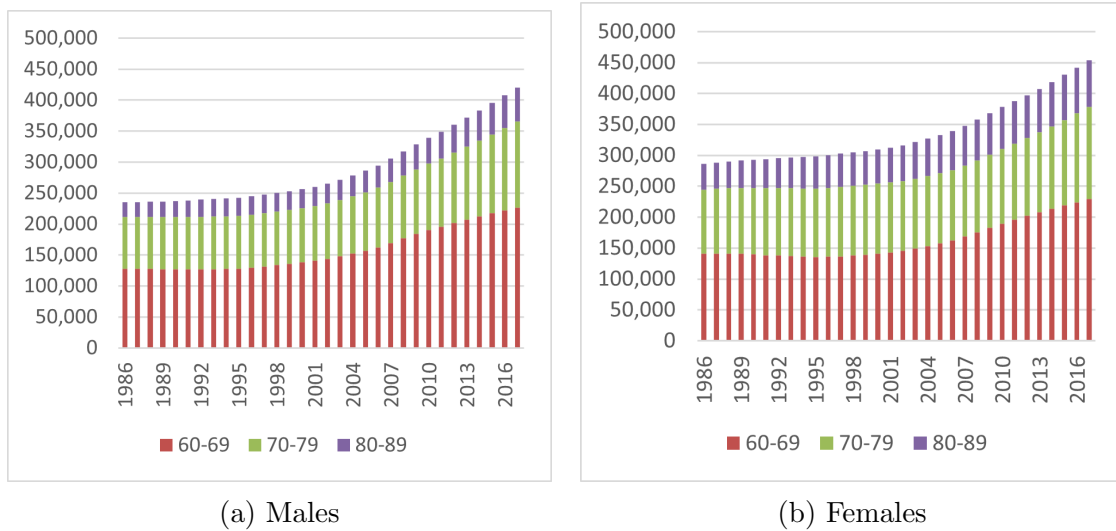


Figure 3.2: Exposures for the 32-year period 1986–2017 by age group for males and females respectively.

Table 3.1 presents the change in exposures between the years 1986 and 2017 by age group and gender. As can be seen from both Figure 3.2 and Table 3.1, the number of people between the ages 60-89 increased substantially over the 32-year period for both males and females. The total exposures increased by c.79% for males (235,197 to 420,190) and c.59% for females (286,319 to 454,292) in the period 1986 to 2017, with the greatest increase seen at older ages.

	Males			Females		
	1986 (000's)	2017 (000's)	% increase	1986 (000's)	2017 (000's)	% increase
Age 60-69	128	226	77%	141	229	62%
Age 70-79	84	140	67%	103	149	43%
Age 80-89	23	54	135%	42	76	81%
Total	235	420	79%	286	454	59%

Table 3.1: Change in exposures from 1986 to 2017 by age group for males and females respectively.

Furthermore, to analyse the impact of seasonal mortality on institutional type living arrangements among the elderly, data on the number of deaths by place of occurrence of death was obtained from the CSO for the period 2013-2017 split by 5-year age bands (ages 60-99), month and year. Finally, data on the number of individuals by marital status from 1986 to 2017, divided into 5-year age bands, as well as information on the month of death from 2014 to 2018, were obtained directly from the CSO. This data was used to assess the impact of marital status on seasonal mortality.

Studies of seasonal mortality in the Northern Hemisphere tend to define winter as the period December to the following February or March. To analyse the seasonal mortality and mortality improvement trends for Ireland the monthly death data for each year was allocated to the four (meteorological) seasons as follows:

Season	Months
Spring	March, April, May
Summer	June, July, August
Autumn	September, October, November
Winter	December, January, February

Table 3.2: Seasons and corresponding months

The winter season, therefore, spans two calendar years. Accordingly, the length of meteorological seasons are fixed: 92 days each for spring and summer, 91 days for autumn and 90 (or 91 in leap years) days for winter. As winters do not nest into calendar years, seasonal mortality data begins with spring 1986 and ends with winter 2016/17 inclusive. Throughout this chapter, year will refer henceforth to the

year in which a season begins e.g. winter 1986 will refer to December 1986, January 1987 and February 1987.

3.3 Methodology

To provide an overview of the seasonality of Irish mortality the monthly death data is first analysed using the Excess Winter Mortality Index (EWMI). Mortality trends are then presented using standardised mortality rates calculated for each season before fitting generalised additive models to the data to model the seasonal mortality trends

3.3.1 Excess Winter Mortality

The Excess Winter Mortality Index (EWMI) is a simple method widely used to illustrate the relative difference between winter and non-winter deaths (Healy (2003) and ONS (2017)) Based on our three-month definition of winter, the Excess Winter Mortality spanning the year x and year y , quantifies the additional deaths occurring in the winter months compared to the average number of deaths during non-winter months and is defined as follows:

$$\text{EWM}_{x|y} = \text{Winter Deaths}_{x|y} - \text{Average Non-Winter Deaths}_{x|y} \quad (3.1)$$

where:

$$\text{Winter Deaths}_{x|y} = \text{Deaths}(\text{Dec})_{\text{year } x} + \text{Deaths}(\text{Jan})_{\text{year } y} + \text{Deaths}(\text{Feb})_{\text{year } y} \quad (3.2)$$

Average Non-Winter Deaths $_{x|y}$:

$$\frac{\text{Deaths}(\text{Aug-Nov})_{\text{year } x} + \text{Deaths}(\text{March-June})_{\text{year } y} + \frac{\text{Deaths}(\text{July})_{\text{year } x} + \text{Deaths}(\text{July})_{\text{year } y}}{2}}{3} \quad (3.3)$$

The Excess Winter Mortality Index expresses the EWM as a percentage of the

average non-winter deaths, illustrating the relative increase in mortality during winter and is defined as:

$$\text{EWMI}_{x|y} = \left(\frac{\text{EWM}_{x|y}}{\text{Average Non-Winter Deaths}_{x/y}} \right) \times 100 \quad (3.4)$$

For the n-year period $i|j$ to $k|l$, the n-year EWMI ($\text{EWMI}_{i|j \rightarrow k|l}$) is calculated based on the sum of the winter deaths and the sum of the average non-winter deaths over the n years. The winter and average non-winter deaths for the years $i|j$ to $k|l$ are calculated as:

$$\text{Winter Deaths}_{i|j \rightarrow k|l} = \sum_{m|n=i|j}^{k|l} \text{Winter Deaths}_{m|n} \quad (3.5)$$

$$\text{Average Non Winter Deaths}_{i|j \rightarrow k|l} = \sum_{m|n=i|j}^{k|l} \text{Average Non Winter Deaths}_{m|n} \quad (3.6)$$

Therefore, for the n-year period $i|j$ to $k|l$, the n-year EWMI is defined as:

$$\text{EWMI}_{i|j \rightarrow k|l} = \left(\frac{\text{EWM}_{i|j \rightarrow k|l}}{\text{Average Non-Winter Deaths}_{i|j \rightarrow k|l}} \right) \times 100 \quad (3.7)$$

where the n-year Excess Winter Mortality is defined as:

$$\text{EWM}_{i|j \rightarrow k|l} = \text{Winter Deaths}_{i|j \rightarrow k|l} - \text{Average Non-Winter Deaths}_{i|j \rightarrow k|l} \quad (3.8)$$

Using the normal approximation for large samples, and assuming that deaths are statistically independent and follow a Poisson distribution, and that EWM is fixed (given its based on population-level data), the 95% confidence interval for EWMI is calculated as:

$$\text{EWMI} \pm 1.96 \times \frac{\text{EWMI}}{\sqrt{\text{EWM}}} \quad (3.9)$$

where the EWMI and the EWM refer to the n-year EWMI and the n-year EWM

respectively.

3.3.2 Seasonal Standardised Mortality Rates (SSMRs)

All cause mortality trends by season are compared using directly age standardised mortality rates standardised to the 2013 European Standard Population (Eurostat (2013)) . The Seasonal Standardised Mortality rates (SSMR) is calculated as follows:

$$SSMR_{s,x,t} = \frac{\sum_x \frac{d_{s,x,t}}{E_{x,t}} * SP_x}{\sum_x SP_x} \quad (3.10)$$

where $d_{s,x,t}$ is the number of deaths at age x in season s in year t , $E_{x,t}$ is the exposed to risk at age x in year t , and SP_x is the 2013 European standard population at age x .

For the winter season, which spans two consecutive calendar years, the exposed to risk is calculated as the weighted average of the exposure for the two consecutive calendar years. Deaths in each season were standardised to 92 days in length. The 2013 European standard population is provided in five-year age bands between ages 60 and 89, and for calculation purposes, it is assumed that the population was split equally across all five ages in each age band. Using the normal approximation for large samples, and assuming that deaths are statistically independent and that the SSMR follows a Binomial distribution, the 95% confidence interval for EWMI is calculated as:

$$SSMR_{s,x,t} \pm 1.96 \sqrt{\text{Var}(SSMR_{s,x,t})} \quad (3.11)$$

$$\text{where } \text{Var}(SSMR_{s,x,t}) = \sum \left[\left(\frac{\frac{d_{s,x,t}}{E_{x,t}} \left(1 - \frac{d_{s,x,t}}{E_{x,t}} \right)}{E_{x,t}} \right) * \left(\frac{SP_x}{\sum_x SP_x} \right)^2 \right] \quad (3.12)$$

The SSMR's averaged over n years provide a smoother estimate of the mortality rates. The n -year average SSMR in year t for season s and age group x is calculated as:

$$\overline{SSMR}_{s,x,t,n} = \frac{\sum_{k=t}^{t+n-1} SSMR_{s,x,k}}{n} \quad (3.13)$$

A mortality improvement factor measures the reduction in mortality rates from one time period to the next. The n -year mortality improvement factor in year t for season s and age group x is defined as:

$$SMI_{s,x,t,n} = 1 - \left(\frac{SSMR_{s,x,t}}{\overline{SSMR}_{s,x,t-n}} \right)^{\frac{1}{n}}, \quad n \leq 5 \quad (3.14)$$

Using the 5-year average SSMRs (equation 3.13), the annualised summer and winter improvements for age group x over the entire period (1986–2016 for summer and 1986/87–2016/17 for winter) is defined as:

$$\text{Summer: } SMI_{\text{summer},x,1986-2016} = 1 - \left(\frac{(\overline{SSMR}_{\text{summer},x,2012,5})^{\frac{1}{26}}}{(\overline{SSMR}_{\text{summer},x,1986,5})^{\frac{1}{26}}} \right) \quad (3.15)$$

$$\text{Winter: } SMI_{\text{winter},x,1986/87-2016/17} = 1 - \left(\frac{(\overline{SSMR}_{\text{winter},x,2012/13,5})^{\frac{1}{26}}}{(\overline{SSMR}_{\text{winter},x,1986/87,5})^{\frac{1}{26}}} \right) \quad (3.16)$$

3.3.3 Generalised Additive Models

Generalised Additive Models (GAMs) are used to smooth the seasonal mortality data to analyse trends by season. GAMs were originally developed by Trevor Hastie and Robert Tibshirani in 1986 (1986,1993). The GAM framework is based on the following assumptions:

- Relationships between the individual predictors and the dependent variable

follow smooth patterns that can be linear or nonlinear;

- You can estimate these smooth relationships simultaneously and then estimate the dependent variable by adding up these relationships.

GAMs extend generalized linear models (GLM) which are widely used for modelling mortality. Generalized linear models (McCullagh and Nelder (1989b) and Nelder and Wedderburn (1972)) are mathematical extensions of linear models for distributions of non-normal response variables and non-linear transformations, providing a method of estimating a function of the mean of the conditional response variable as a linear combination of the set of predictor variables, x_i , or

$$g(E[Y | X]) = g(\mu) = \eta(x) = \beta_0 + \sum_{i=1}^p \beta_i x_i \quad (3.17)$$

where the function of the conditional response mean, $g(\mu)$, is referred to as the link function and is considered to be a linear function of the predictor variables, $\eta(x)$, which is referred to as the linear predictor.

GAMs relax the linearity assumptions of GLMs and by allowing the linear predictor to include smooth functions of the covariates GAMs allow complex relationships to be implemented while still retaining a simple linear relationship amongst the predictor variables. Deaths are assumed to follow a Poisson distribution and the following 2-Dimensional GAM was fitted to the mortality data for each season:

$$d_{ij} \sim \text{Poisson}(E_{ij}^c \mu_{ij}) \quad (3.18)$$

$$\eta_{ij} = \log(\mu_{ij}) = \beta_0 + f(\text{Age}_i, \text{Year}_j) + \log(E_{ij}^c) \quad (3.19)$$

where i and j indicate the current age and year respectively, d is the number of deaths, μ is the force of mortality, E is the years of exposure, and f is a two-dimensional smooth function implemented using thin plate regression splines (Wood (2003) and Wood (2006)). Separate models were implemented for each season for males and females, and the number of days in each season was standardised to 92

days. The GAMs were implemented using R (R Development Core Team (2014)), version 3.1.2 package `mgcv` version 1.8-32 (Wood (2020)).

The smooth functions are implemented using thin plate regression splines (Wood (2003) and Wood (2006)). Unlike other spline-based smoothing functions, thin plate regression splines avoid the need to choose “knot” locations, and they extend relatively easily to multiple dimensions. The degrees of freedom (DOF) in the model specification determine the smoothness of the smooth functions. When specifying the DOF for a smooth function in a GAM, a trade-off is needed between a sufficiently high DOF to correctly capture variations in the data and a low DOF to allow the overall trend in the data to be modelled.

The models were fitted using penalised maximum likelihood, where the model likelihood is modified by the addition of a penalty for each smooth function, penalising its “wiggleness.” Each penalty is multiplied by an associated smoothing parameter, which controls the trade-off between goodness of fit and smoothness. The application of the penalties during fitting reduces the DOF in the model specification to yield the effective DOF for the smooth functions. The smoothing parameters are estimated automatically from the data. The DOF in the model specification place an upper limit on the flexibility of a smooth function, while the smoothing parameters determine the effective DOF within that limit. The lower the effective DOF, the smoother the resulting smooth function will be.

The choice of DOF for the smooth functions in the GAM specification is not generally critical as long as they are sufficiently large to model the underlying smooth structure, as the penalisation process determines the effective DOF. DOF in the R package `mgcv` are specified using the parameter k in the `gam` function, where $k = \text{DOF} - 1$. The GAMs were initially fitted with $k = 100$. The resulting models were checked for appropriateness using the provided function `gam.check()` and the residual plots were checked for randomness.

3.4 Results

3.4.1 Excess Winter Mortality Index

Figure 3.3 plots the n-year EWMI for three age groups 60-69, 70-79 and 80-89 for males and females respectively and is calculated for the 3 time periods 1986–1995 ($n = 10$ years), 1996–2005 ($n = 10$ years) and 2006–2017 ($n = 12$ years).

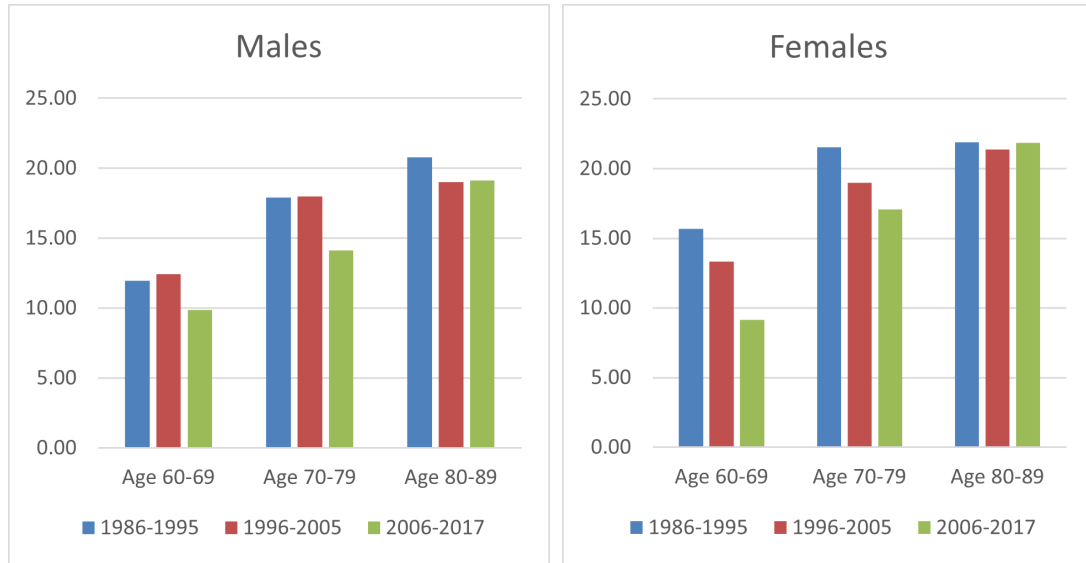


Figure 3.3: EWMI plots for age groups 60-69, 70-79, and 80-89 for males and females, respectively, for the three durations 1986-1995, 1996-2005, and 2006-2017.

The results from Figure 3.3 highlight that for both males and females, excess winter mortality increases with age. While all age groups experience excess mortality during winter months, the magnitude of this increase is more pronounced among older age groups. This trend underscores the vulnerability of older individuals to winter conditions (Hajat (2017)). Furthermore, females were generally more affected by excess winter mortality compared to males, except for those aged 60–69 during the 2006–2017 period. This trend aligns with findings in the literature, which indicate a greater vulnerability of females to winter-related mortality risks (Campbell (2017) and Bogdanović et al. (2013)).

Over time, a general decline in excess winter mortality has been observed for both genders. This reduction could be attributed to various factors, including improved

healthcare, better housing insulation, vaccination programs, and increased public awareness about the risks associated with cold weather (Healy (2003), Davie et al. (2007), and Kunst, Looman, and Mackenbach (1991)).

Table 3.3 presents the numerical values of the EWMI figures shown in Figure 3.3, along with their 95% confidence intervals, indicating the variability of these values.

Period	Duration (years)	60-69	70-79	80-89
Males				
1986-1995	10	11.9 (± 0.75)	17.9 (± 0.71)	20.8 (± 0.91)
1996-2005	10	12.4 (± 0.86)	18.0 (± 0.77)	19.0 (± 0.85)
2006-2017	12	9.9 (± 0.74)	14.1 (± 0.69)	19.1 (± 0.75)
Females				
1986-1995	10	15.7 (± 1.11)	21.6 (± 0.83)	21.9 (± 0.83)
1996-2005	10	13.3 (± 1.17)	19.0 (± 0.91)	21.4 (± 0.79)
2006-2017	12	9.2 (± 0.89)	17.1 (± 0.90)	21.9 (± 0.75)

Table 3.3: EWMI values for age groups 60-69, 70-79, and 80-89 for males and females across the periods shown.

3.4.2 Seasonal Standardised Mortality Rates (SSMRs)

Figure 3.4 presents the seasonal standardised mortality rates (SSMRs) for males and females for age groups 60-69, 70-79 and 80-89 over the period 1986-2016 for spring, summer and autumn and the period 1986/87 – 2016/17 for winter. As expected, mortality rates have declined for both males and females across all age groups and in each season over the entire period. Mortality is highest in the winter followed in descending order by mortality in the spring, autumn and summer. Mortality in these age groups therefore tends to be higher in the first half of the year relative to the mortality in the second half of the year and the assumption of uniform distribution of deaths (UDD) does not hold at these ages. For both males and females, the gap between summer and winter mortality increases with increasing age.

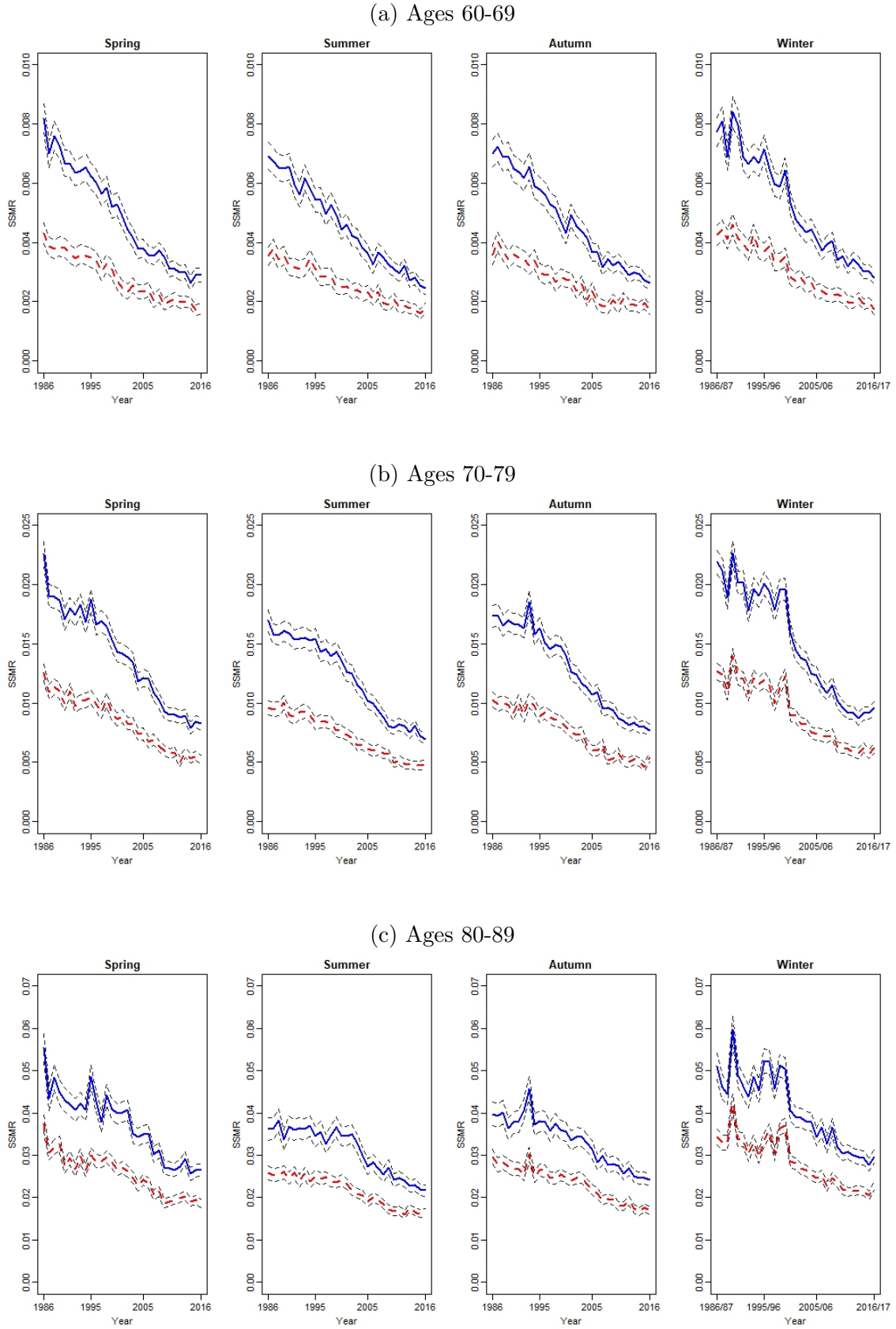


Figure 3.4: SSMR's for age groups 60–69, 70–79, and 80–89 for males (—) and females(--) with associated 95% Confidence Intervals (--) from 1986–2016 for Spring, Summer, and Autumn, and from 1986/1987–2016/2017 for Winter.

Figures 3.5 and 3.6 present the corresponding 5-year average annual improvements in the standardised summer and winter mortality rates for males and females for age groups 60-69, 70-79 and 80-89. The improvement factors were averaged over a 5 year period to provide a smoother estimate (see equation 3.14). For all age groups the range of the annualised improvements was more volatile in the winter ranging from approximately -4.0% to 7.0% for both males and females. The corresponding range of annualised summer improvements was approximately -2.0% to 4% for both males and females. Winter mortality improvements dominated the period 1998 – 2003 for all ages bands for both males and females.

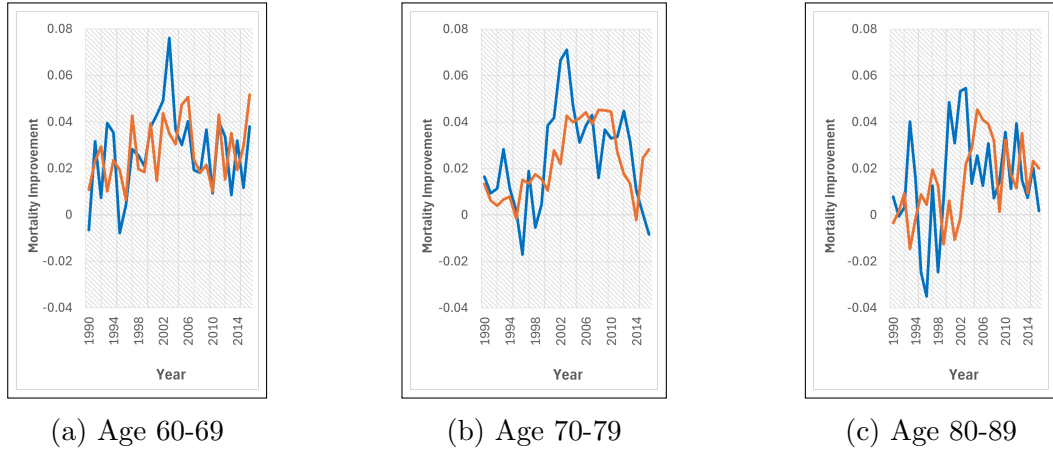


Figure 3.5: 5-year average annual mortality improvements for males in age groups 60-69, 70-79, and 80-89 during summer (1986-2016) (—) and winter (1986/87 - 2016/17) (—).

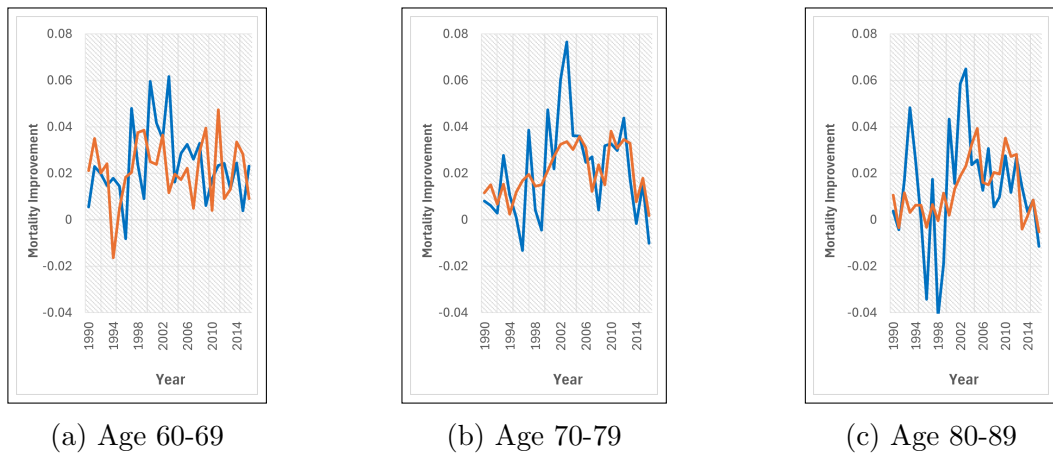


Figure 3.6: 5-year average annual mortality improvements for females in age groups 60-69, 70-79, and 80-89 during summer (1986-2016) (—) and winter (1986/87 - 2016/17) (—).

Mortality rates are highest in the winter and improvements in winter mortality will therefore have a greater impact than summer mortality improvements on the overall annual improvement rates. Table 3.4 presents the annualised improvements for the summer and winter seasons for the complete period (using equations 3.15 and 3.16). From Table 3.4 we can see that overall improvements were greater for males relative to females in both the summer and winter seasons. As a result of the higher rates of improvement for males the gap between male and female mortality declined in both seasons. Overall improvements were higher in the winter relative to the summer for all age groups for both males and females.

Age Group	Summer		Winter	
	Males	Females	Males	Females
60-69	3.22%	2.54%	3.36%	2.91%
70-79	2.76%	2.52%	3.02%	2.69%
80-89	1.72%	1.58%	1.97%	1.80%

Table 3.4: Annualised summer and winter mortality improvements for males and females by age group for the period 1986-2016 (summer) and 1986/87-2016/17 (winter).

3.4.3 Generalised Additive Models

Seasonal mortality by age and year was modeled using Poisson 2-Dimensional GAMs for the period 1986–2016 (spring, summer, autumn) and 1986/87–2016/17 (winter), separately for males and females, based on equation 3.19. Separate models were fitted for each season and gender. Results are presented in Tables 3.5 and 3.6 for males and females respectively.

	Time Period Fitted	Intercept	Value of k in GAM model	Effective degrees of freedom for smooth functions	Adjusted R^2	Deviance Explained
Spring	1986-2016	-4.290880	200	41.50	0.907	98.6%
Summer	1986-2016	-4.418250	100	28.13	0.894	98.4%
Autumn	1986-2016	-4.374328	100	21.07	0.888	98.3%
Winter	1986/87-2016/17	-4.216639	200	48.65	0.888	98.3%

Table 3.5: Parameter values and goodness of fit statistics for the 2D GAMs used to smooth seasonal mortality rates for males in Ireland.

	Time Period Fitted	Intercept	Value of k in GAM model	Effective degrees of freedom for smooth functions	Adjusted R^2	Deviance Explained
Spring	1986-2016	-4.762897	200	34.50	0.943	98.7%
Summer	1986-2016	-4.889606	100	21.90	0.940	98.6%
Autumn	1986-2016	-4.852680	100	24.53	0.936	98.5%
Winter	1986/87-2016/17	-4.676692	200	55.08	0.937	98.6%

Table 3.6: Parameter values and goodness of fit statistics for the 2D GAMs used to smooth seasonal mortality rates for females in Ireland.

Figures 3.7 and 3.8 present the corresponding residual plots for males and females by season. Residuals exhibited a random pattern, indicating an adequate model fit.

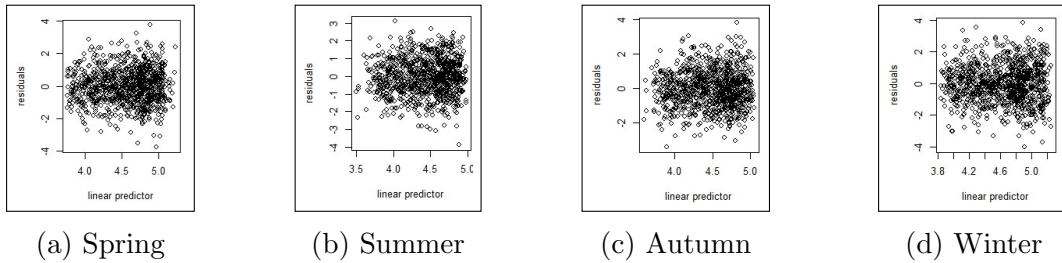


Figure 3.7: Residual plots for males by season after fitting 2D GAMs.

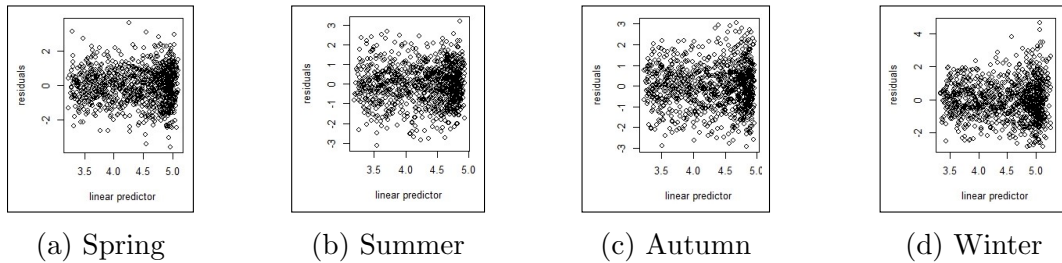


Figure 3.8: Residual plots for females by season after fitting 2D GAMs.

For comparative purposes, Figures 3.9 and 3.10 present the crude rates, SSMRs, and fitted GAM rates for winter and summer, for both males and females at ages 65, 75, and 85. The fitted rates from the GAM are relatively smooth across all ages and genders. However the female crude rates and SSMRs tend to show higher volatility than the corresponding rates for males. As previously identified, the crude mortality rates in the winter are generally more volatile than the summer across all ages for both males and females. For males, the difference or gap between summer and winter mortality increases with increasing age and a similar trend can be seen for females. The smooth GAM rates show a steady decline in the summer season for all ages and genders but this is not the case for the winter season.

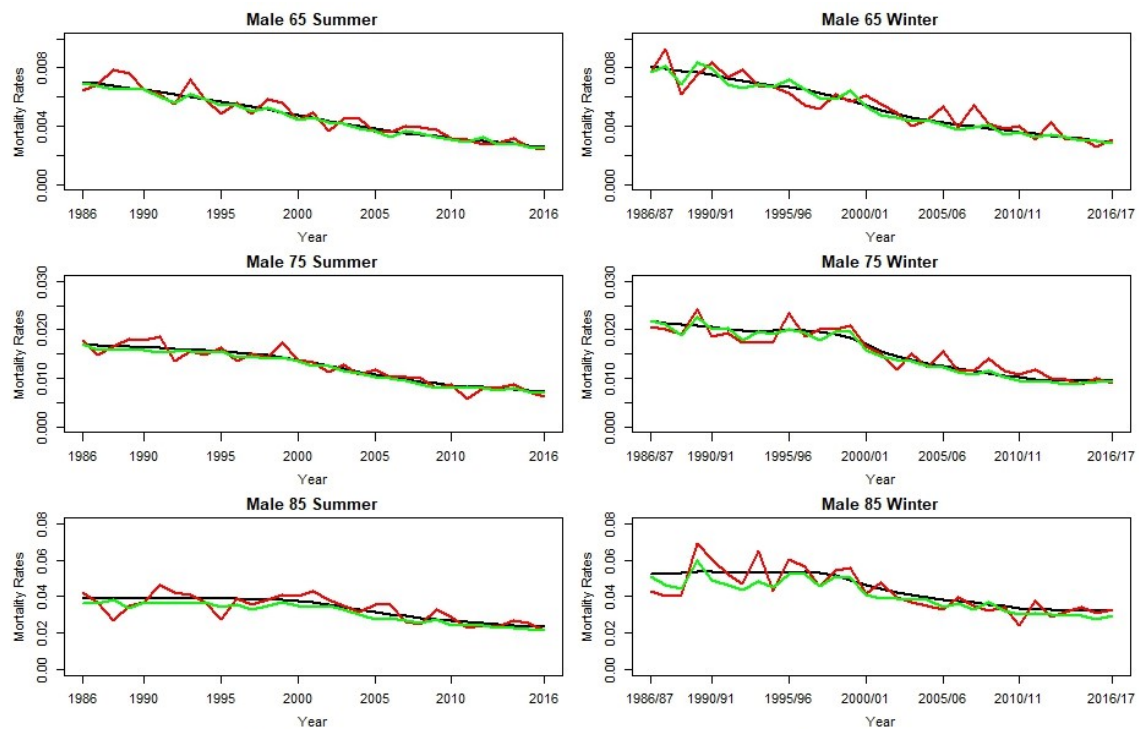


Figure 3.9: Comparison of crude rates (—), SSMRs (—), and fitted GAM rates (—) for ages 65, 75, and 85 for males for the summer over the period 1986-2016 & the winter over the period 1986/87-2016/17.

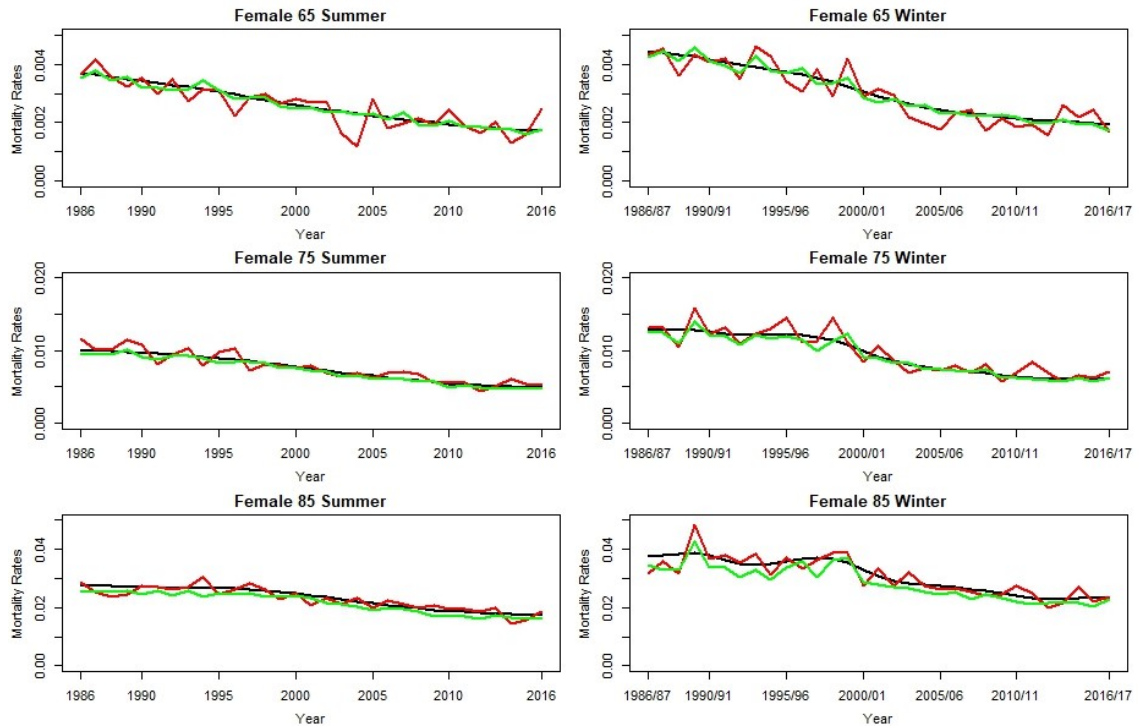


Figure 3.10: Comparison of crude rates (—), SSMRs (—), and fitted GAM rates (—) for ages 65, 75, and 85 for females for the summer over the period 1986-2016 & the winter over the period 1986/87-2016/17.

Figures 3.11 and 3.12 present heatmaps of the mortality improvements from the GAM's in the summer season (over the period 1986-2016) and winter season (over the period 1986/87-2016/17) for males and females respectively. The heatmaps were generated using the Continuous Mortality Investigation (CMI) of the Institute and Faculty of Actuaries, UK Excel macro for heatmaps (CMI (2015)). Winter mortality improvements peaked around the turn of the century for both males and females. The peak of the summer improvements was slightly later and was less significant than the winter peak. Throughout the period, improvement rates were generally higher for males than females in both summer and winter, with the most pronounced differences occurring during the summer season.

One potential reason for the mortality improvements at the turn of the century was the rapid economic growth during this period. As described in section 3.1, Ireland saw substantial economic growth in the 1990s and early 2000s, which led to significant increases in public health expenditure. In particular, in July 2001 free medical cards were introduced for individuals aged 70 and over, providing automatic

entitlement to a medical card regardless of income (Kenneally (2009)). Additionally, following a particularly bad European winter flu season in 1999/2000 (Houston (2001), Boseley (2008), and Gregoriadis (1999)), the seasonal flu vaccine became freely available to all at-risk groups (Crosbie (2000)).

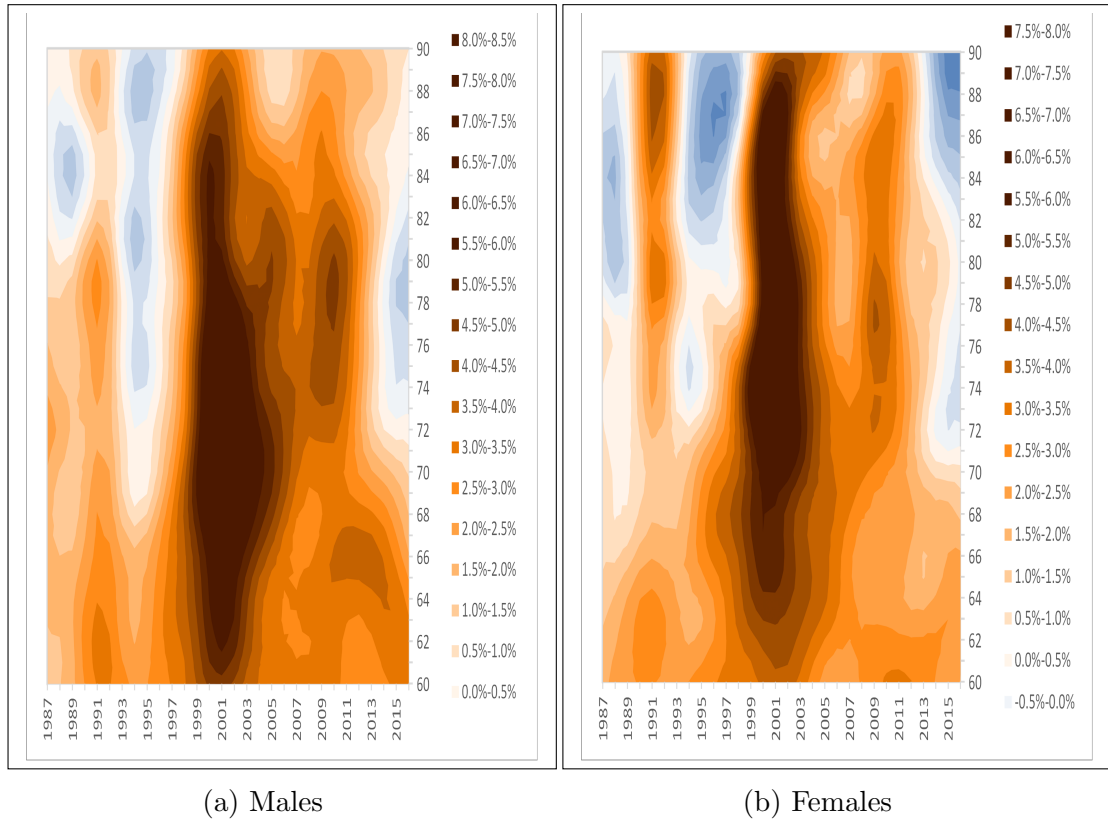


Figure 3.11: Annualised winter mortality improvements from 1986/87–2016/17.

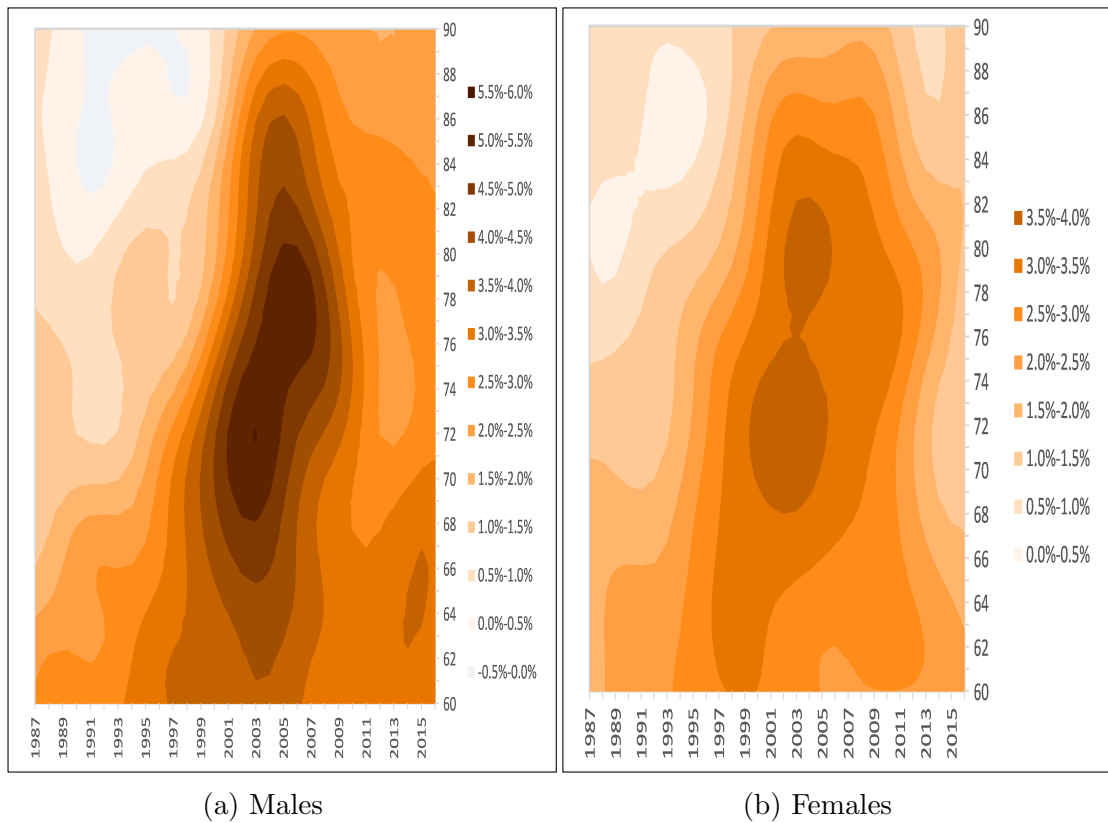


Figure 3.12: Annualised summer mortality improvements from 1986–2016.

3.5 Mortality projections allowing for seasonality

At older ages, mortality trends differ by season and this should be considered in future mortality projections at older ages. In particular, given the impact of seasonality on Irish mortality, Irish mortality projections at older ages should allow for seasonality. As previously discussed, mortality trends during non-winter months are less volatile compared to winter mortality trends. This result aligns with other published literature that shows a higher fluctuation in mortality during the colder months (Telfar-Barnard et al. (2024) and Jones and Ponomarenko (2022)). This is mainly due to the fact that winter mortality is strongly influenced by extreme weather events and the severity of the prevailing influenza strain, both of which can fluctuate from year to year (Ballester et al. (2016) and Fuhrmann (2010)).

Consequently to allow for the impact of seasonality, a two-step process was used to project future mortality at older ages:

1. Non-winter mortality trends were projected separately for both males and females.
2. Annual mortality rates were obtained by adjusting the projected non-winter mortality rates to account for excess winter mortality under a range of scenarios.

Any sensitivity analysis for excess winter deaths should incorporate scenarios with both higher and lower levels of excess winter mortality to account for potential future trends. Factors such as improvements in the effectiveness of the flu vaccine, improved healthcare, and warmer homes could reduce future excess winter deaths, to the level experienced in Scandinavian countries (Laake and Sverre (1996) and Walkowiak, Walkowiak, and Walkowiak (2024)). Alternatively as some predict, an increase in respiratory viruses like Covid-19 (whose impact is generally more severe in the winter) could lead to higher excess winter mortality in the future (Gavi (2021) and Public Health (2021)).

3.5.1 Methodology

Non-winter mortality rates were projected using the M7 Age Period Cohort (APC) stochastic mortality model (Cairns et al. (2009)) which is suitable for modelling mortality at older ages. This model is an extension of the Cairns-Blake-Dowd model and is suitable for modelling mortality at older ages as it allows for non-linearity at these ages due to the inclusion of an additional quadratic term (Cairns et al. (2009)). The model's overall stochastic and robust nature effectively handles uncertainty, which is important for projecting seasonal mortality rates at older ages, where data is often sparse (Plat (2009), Wong, Forster, and Smith (2023), Cairns et al. (2011a), and Villegas, Kaishev, and Millossovich (2018)). Deaths are assumed to follow a binomial distribution:

$$D_{t,x} \sim \text{Binomial}(E_{t,x}^c, \hat{m}_{t,x}) \quad (3.20)$$

where:

- $D_{t,x}$: Number of deaths at time t for age x
- $E_{t,x}^c$: The Central Exposure-to-risk (i.e., the number of individuals at risk of dying) at time t and age x
- $\hat{m}_{t,x}$: Estimated mortality rate at time t for age x

The general formula of the model is:

$$\text{logit } q(t, x) = \beta_x^{(1)} \kappa_t^{(1)} + \beta_x^{(2)} \kappa_t^{(2)} + \beta_x^{(3)} \kappa_t^{(3)} + \beta_x^{(4)} \gamma(c). \quad (3.21)$$

where $\beta_x^{(i)}$ relate to the Age effect, $\kappa_t^{(i)}$ relate to the Period effect and $\gamma(c)$ relate to the cohort effect.

For the M7 model, the following simple parametric forms are assumed for $\beta_x^{(1)}$, $\beta_x^{(2)}$, $\beta_x^{(3)}$, and $\beta_x^{(4)}$ as described by Cairns et al. (2009), where:

$$\beta_x^{(1)} = 1, \quad \beta_x^{(2)} = (x - \bar{x}), \quad \beta_x^{(3)} = [(x - \bar{x})^2 - \hat{\sigma}_x^2], \quad \beta_x^{(4)} = 1.$$

Following on from the Beta forms outlined above, the first three terms of the model are explained as follows:

- $\beta_x^{(1)} \kappa_t^{(1)}$: Captures changes in mortality across time that impact all ages similarly.
- $\beta_x^{(2)} \kappa_t^{(2)}$: Adjusts for how mortality changes differently across various ages.
- $\beta_x^{(3)} \kappa_t^{(3)}$: Adds a curvature to age-related mortality trends to fit data more accurately and to account for non-linear mortality trends in populations. This is especially useful when mortality patterns deviate from linearity like in older ages (Cairns et al. (2009)).

Additionally, the model includes a Cohort effect ($\gamma(c)$), which reflects generational differences in mortality improvements, where $c = t - x$ (cohort or year of birth). The model was fitted using the StMoMo package in R, developed by Villegas et al. (2018) and parameter estimates are obtained by maximising the model log-likelihood.

3.5.2 Fitting the model

The M7 APC model was fitted to 'non-winter' data for individuals aged 60–95 over the years 1986–2017. Non-winter data includes deaths in months March - November (inclusive). Figure 3.13 presents a heat map of the residuals after fitting the model to the male and female 'non-winter' data. As shown, the pattern appears random, and the standardised residuals range between -3 and +3, indicating a relatively narrow range and thus a good fit.

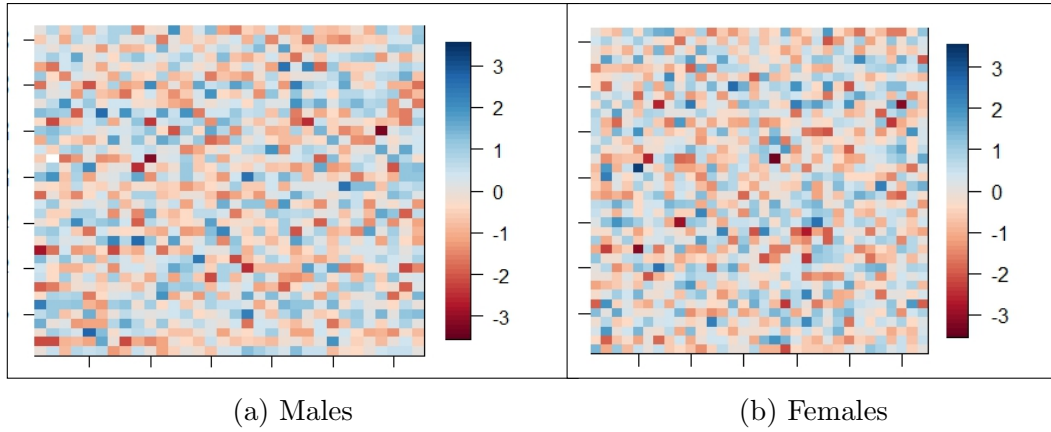


Figure 3.13: M7 residual heat maps for the non-winter data over the age range 60-95 for males and females over the period 1986-2017.

Figure 3.14 presents the age effects ($\beta_x^{(i)}$), period effects ($k_t^{(i)}$), and cohort effect (γ_{t-x}) after applying the model to the 'non-winter' data for both males and females.

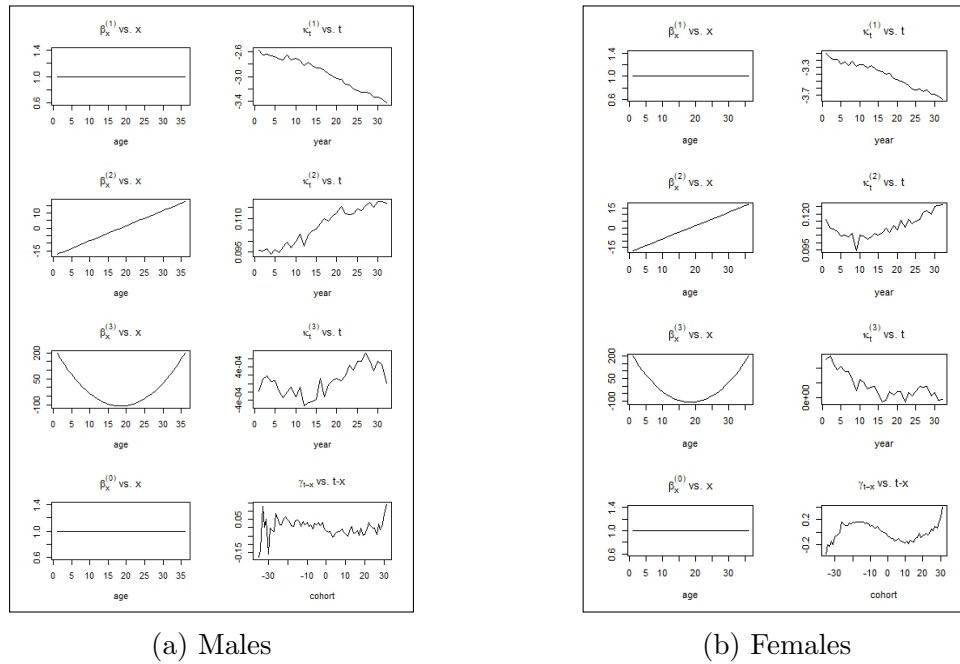


Figure 3.14: Age effects ($\beta_x^{(i)}$), period effects ($k_t^{(i)}$), and cohort effect (γ_{t-x}) from M7 stochastic model to non-winter data over the age range 60–95 for males and females during 1986–2017.

3.5.3 Forecasting using the model

In order to assess the potential impact of seasonal patterns on future mortality, projections of future mortality rates are required. In this section mortality is forecast over the 23 year period 2018 - 2040 (inclusive).

Forecasting of mortality rates requires modeling of the period and cohort effects using time series techniques. Figures 3.15 and 3.16 present the forecasts of the period and cohort effects for ages 60-95 over the period 2018-2040 for males and females. The solid centre black line represent the central forecast, the red fans represent the 80% confidence intervals and cyan fans represent the 95% confidence intervals.

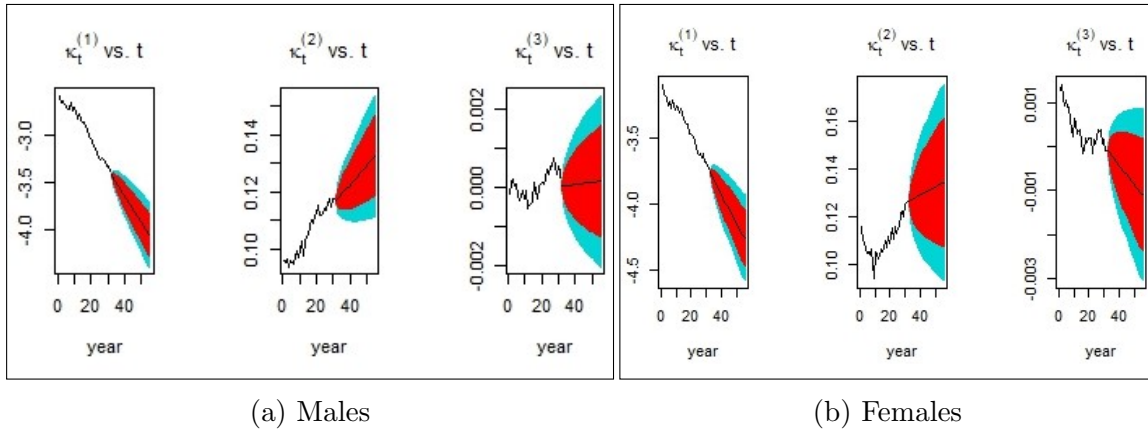


Figure 3.15: Projected Kappa plots for non-winter mortality rates from 2018 to 2040, based on the M7 stochastic mortality model, for males and females aged 60-95, with data fitted from 1986 to 2017.

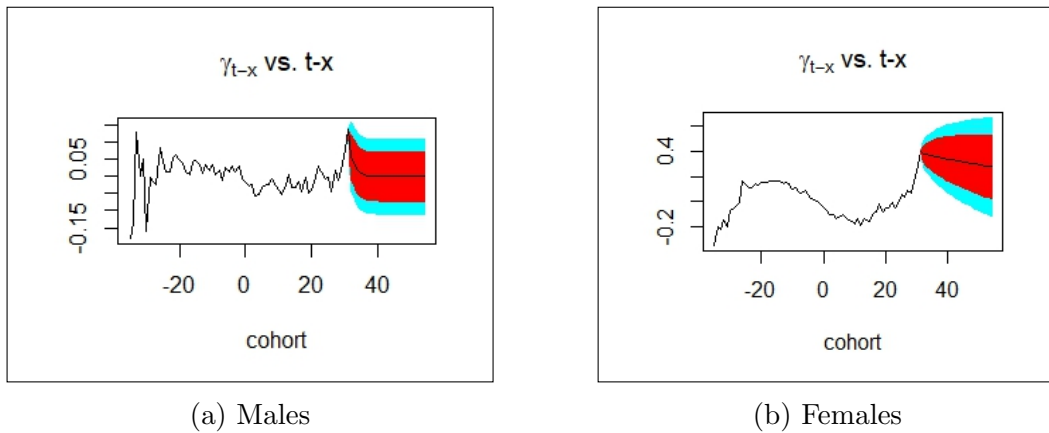


Figure 3.16: Projected cohort plots for non-winter mortality rates from 2018 to 2040, based on the M7 stochastic mortality model, for males and females aged 60-95, with data fitted from 1986 to 2017.

Having estimated the non-winter mortality rates for males and females in 2040, the next step is to understand how the annual 2040 mortality rates may look under different seasonal scenarios. Three scenarios were considered based on the seasonal gap between the annual and non-winter mortality over the most recent period 2015-2017. The three scenarios considered are as follows:

- The seasonal mortality gap decreases by 50%
- The seasonal mortality gap remains constant
- The seasonal mortality gap increases by 50%

The 2015–2017 period was chosen to calculate the seasonal gap as it offered the most recent data available at the time of carrying out this analysis. The seasonal mortality gap was measured as follows for each age x from age 60-95:

$$\text{Seasonal gap}_{x,2015-2017} = \frac{\sum_{t=2015}^{2017} D_{x,t}^{\text{Annual}}}{\sum_{t=2015}^{2017} D_{x,t}^{\text{Non-Winter}}} - 1 \quad (3.22)$$

where:

$D_{x,t}^{\text{Annual}}$ is the total number of deaths for age x in year t over the full calendar year,

$D_{x,t}^{\text{Non-Winter}}$ is the total number of deaths for age x in year t over the non-winter months,

$\text{Seasonal gap}_{x,2015-2017}$ represents the average annual gap between the annual mortality rate and the non-winter mortality rate for age x over the period 2015-2017.

While the seasonal mortality gap by single year of age generally increased with age, it was quite volatile over this 3-year period. Therefore, the seasonal mortality gap was smoothed using a rolling average as follows:

$$\text{Smoothed Seasonal Gap}_x = \frac{1}{11} \sum_{a=x-5}^{x+5} \text{Seasonal gap}_{a,2015-2017}, \quad \text{for } x = 65, 61, 62, \dots, 90 \quad (3.23)$$

Figure 3.17 presents the crude and smoothed mortality gap between the annual mortality rate and the non-winter rate for males and females aged 65-90. As evident from the plots, smoothing has significantly reduced the volatility of the crude gap while preserving the upward trend of an increasing gap with age.

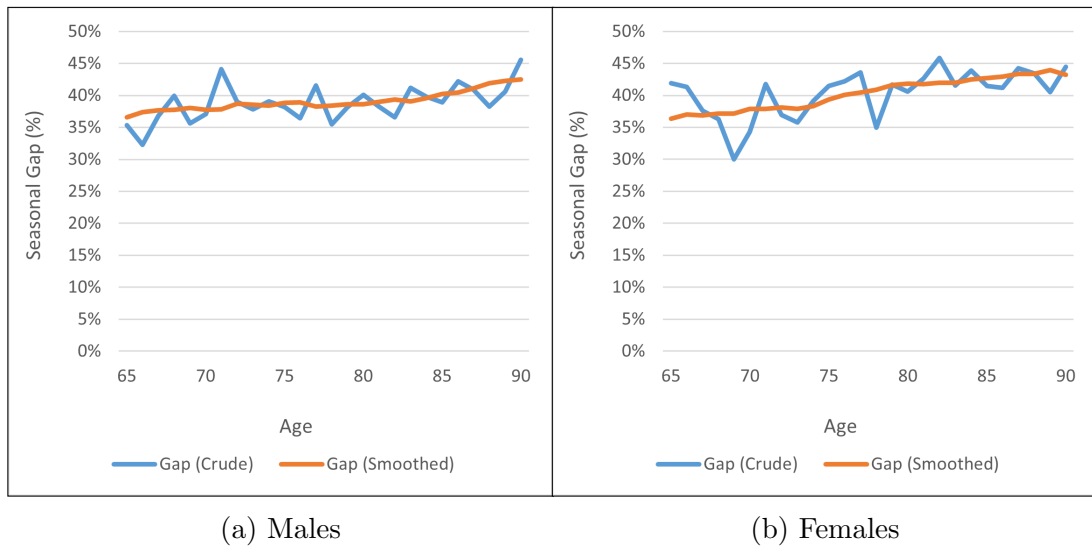


Figure 3.17: Seasonal Mortality gap (%) between the annual mortality rate and the non-winter mortality rate for ages 65–90 for males and females, based on data from 2015–2017.

For the sensitivity testing the annual mortality rate in 2040 was calculated for each age x from 65-90 as follows:

$$\text{Annual Mortality Rate}_x = \text{Non Winter Mortality Rate}_x \times (1 + f \times \text{Smoothed Gap}_x), \quad (3.24)$$

where f represents a multiplicative factor and takes values of 50% and 100% and 150% representing the three seasonal scenarios.

Figure 3.18 presents the 2040 ASMR for males and females, grouped in 5-year age bands from 65 to 89, for the 3 scenarios described above and shows the extent to which the ASMR varies depending on the level of excess winter mortality. These

rates were standardised relative to the European Standard Population 2013 (ESP 2013) using the same methodology outlined in Section 2.2.3. For comparison, the projected 2040 annual mortality rate (both winter and non winter) from the M7 model is also included as a benchmark. As expected, this benchmark generally aligns with the Non-Winter 2040 Mortality Rate adjusted by a 100% gap, particularly for younger age groups. Among older age groups, the Non-Winter mortality rate with a 100% gap slightly exceeds the benchmark for males but remains lower for females. This suggests for older age groups, that the mortality gap observed during the 2015–2017 period (the time period the mortality gap is based on) slightly differs from the implied gap derived from the M7 model, which is based on a significantly longer time-frame from 1986 to 2017.

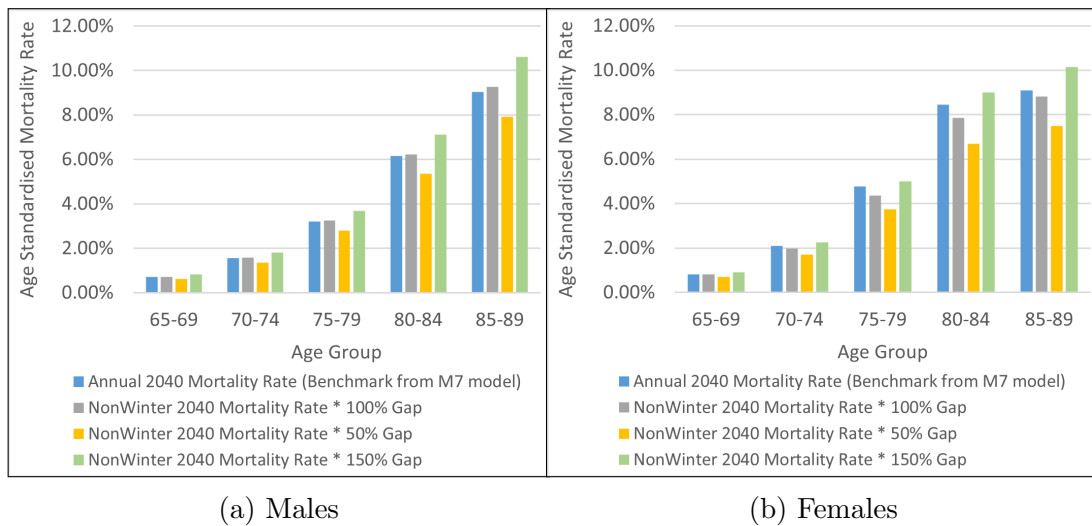


Figure 3.18: ASMRs in 2040 for various seasonal mortality gap scenarios for males and females respectively.

Figure 3.19 presents the relative percentage change in the ASMR for three scenarios—mortality gaps of 100%, 50%, and 150% in comparison to the benchmark annual projected mortality rate for 2040, obtained directly from the M7 model for both males and females. In the 150% mortality gap scenario (i.e., higher excess winter mortality), males experience a greater impact than females, whereas in the 50% gap scenario (i.e. lower excess winter mortality), females see a greater overall reduction in mortality rates compared to males.

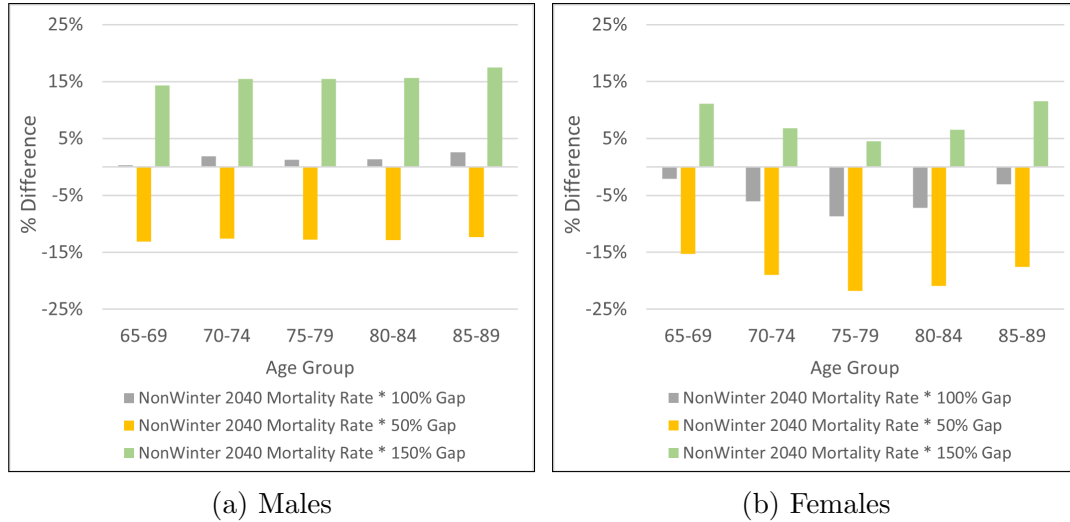


Figure 3.19: Relative % change in the ASMR compared to the base annual 2040 projected mortality rate from the M7 model by age group for the 100%, 50%, and 150% seasonal mortality gap scenarios.

3.6 Factors impacting Excess Winter Mortality

Mortality is known to vary by place of occurrence of death and by marital status. This chapter concludes with a high level analysis of the impact of these factors on seasonal mortality in Ireland via the impact on EWM. The results presented in this section are included only to offer background context rather than serve as a basis for detailed analysis.

3.6.1 Excess Winter Mortality by Place of Occurrence of Death

Residents of nursing homes or other institutions are more vulnerable to infectious diseases including influenza and other respiratory diseases which typically peak in winter (McElhaney (2008), Strausbaugh and Joseph (2000), and Thompson et al. (2003)). Changing patterns of living arrangements at older ages may impact on seasonal mortality trends. To analyse differences in seasonal mortality between individuals residing in nursing homes or other institutions and those living at home, the location of death is utilised as a proxy for their living arrangements.

Figure 3.20 shows the number of deaths for age groups 60–69, 70–79, 80–89, and

90–99 between 2013-2017 for those in institutional care (nursing homes & community hospitals), domiciliary (at home) and in general and orthopedic hospitals. The proportion of deaths that occur in nursing homes & community hospitals increases with age, accounting for 7.9%, 17.4%, 33.3%, and 48.4% of all deaths in the age groups 60-69, 70-79, 80-89 and 90-99, respectively.

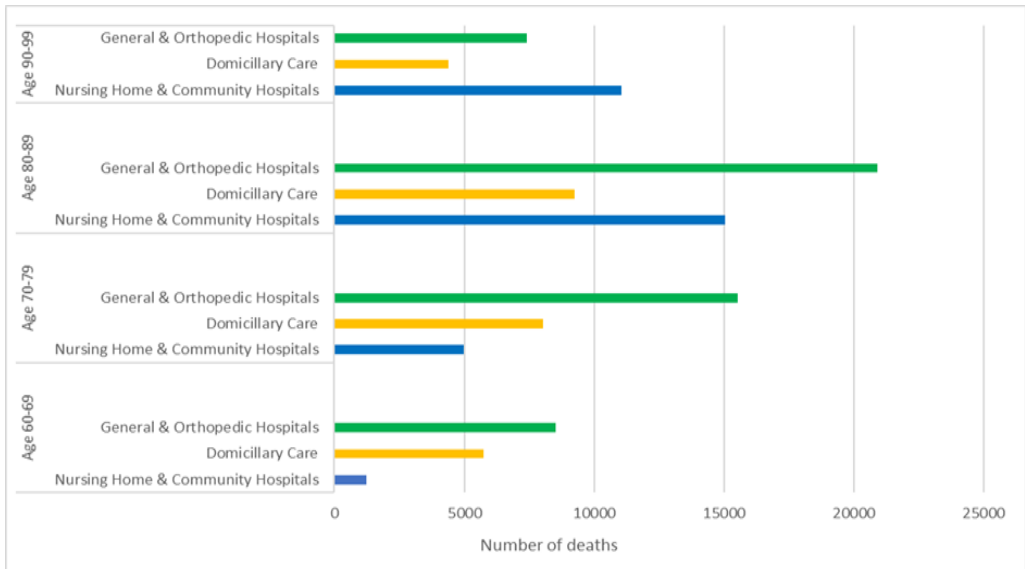


Figure 3.20: Number of Deaths by Place of Death & Age of Death over the 5-year period 2013-2017.

Figure 3.21 presents the EWMI by places of occurrence of death for the three categories described above. Analysis of the impact of EWM on general hospital & orthopedic hospitals is difficult as this group often includes patients admitted from other settings, such as nursing homes or private residences, typically for short stays (The King’s Fund (2012)). Therefore, this category is not considered further. Relative to those living in at home (domiciliary), residents of institutions (nursing homes & community hospitals) experience higher winter morality from age 70 onwards.

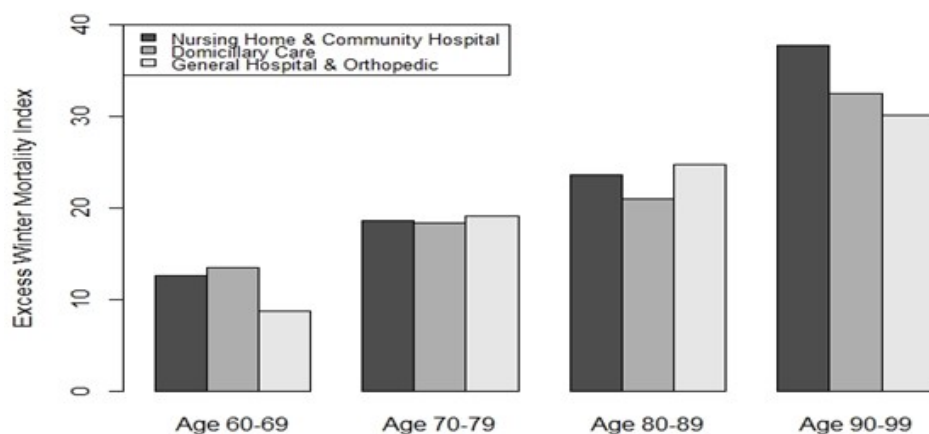


Figure 3.21: EWMI by Place of Occurrence of Death for age groups 60-69, 70-79, 80-89 and 90-99 over the period 2013-2017.

To address the challenges of living in communal environments, the Irish government has introduced several initiatives to support older individuals in aging within their own homes. The 'Home Support Service' helps older individuals remain in their own homes by providing assistance with daily tasks like personal care, dressing, and mobility, tailored to each person's needs (HSE (2024)). Community-based programs, including Meals on Wheels and day services, received funding boosts in 2024 to enhance nutrition and social engagement opportunities (DOH (2024)). Programs like 'The Housing Aid for Older People Grant' provide financial assistance for essential home repairs, such as central heating installation (Housing and Heritage (2024b)). Adaptation grants further help by covering home modifications for mobility and accessibility needs (Housing and Heritage (2024a)). The Fuel Allowance (a means tested benefit) can help older people by providing financial assistance to cover heating costs during the colder months (CitizensInformation (2024)). These initiatives collectively aim to reduce reliance on institutional care for older individuals.

Despite various initiatives to support aging in place, some older individuals still require institutional care. To address this need, the Irish government has long aimed to increase the availability of nursing home spaces. For example, from 1997-2009, the government introduced tax incentives for the construction or refurbishment of

private nursing homes registered with the HSE, which oversees the sector. This initiative led to a significant increase in the number of nursing home beds available across the country (IrishIndependent (2012) and BusinessPost (2005)).

3.6.2 Excess Winter Mortality by Marital Status

Extensive research shows that marriage has a positive impact on life expectancy - in fact marriage was one of the first non-biological factors identified as improving life expectancy (Stibich (2023)). Research has shown that married people tend to have lower mortality rates and longer life expectancy than unmarried people (Balter, Bjerre, and Kallestrup-Lamb (2023), Kaplan and Kronick (2006), Rendall et al. (2011), Lillard and Waite (1995), Manzoli et al. (2007), and Shurtleff (1955)). Possible explanations for the beneficial effects of marriage can include a sense of greater social and financial support, overall healthier behavioral patterns, and self-selection in which healthier individuals tend to marry (Kim and McKenry (2002)). These benefits are greater among men than among women and in younger than in older age groups (e.g., they decrease after the age of 65) (Murphy, Grundy, and Kalogirou (2007) and Franke and Kulu (2018)).

In contrast, transitions out of marriage, such as becoming divorced or widowed, are stressful life events that have been associated with poor health and survival outcomes (Manzoli et al. (2007)). According to Eurostat, the Republic of Ireland has one of the lowest divorce rates in Europe. In 2016, the crude divorce rate in the Republic of Ireland is 0.7 a year for every 1,000 people compared with 1.8 for the UK and 1.9 across all EU countries (Eurostat (2019)). However similar to the broader trend seen in many western world countries and as a result of less prohibitive divorce legislation passed in 2019, the divorce rate in Ireland has been increasing in recent years (The Family Practice (2023)).

Research indicates that widowed individuals tend to experience slightly poorer health compared to those who are married (Sullivan and Fenelon (2014)). This problem appears to have worsened in recent years, potentially due to a decline in

community support and extended family networks that historically provided assistance. Widowed individuals today are more likely to experience isolation (Stibich (2023)). Increasing life expectancy, combined with shifts in family dynamics such as higher divorce rates, increased cohabitation, non-marital births, and solo-living is contributing to greater diversity in family structures (Esteve et al. (2020) and Carr and Utz (2020)).

Figure 3.22 presents the percentage of single males and females in Ireland across various age groups from 1986 to 2016. The percentage of single individuals aged 25-34 has increased significantly during this period. A similar upward trend is observed among those aged 35-44, though the increase is considerably smaller compared to the 25-34 age group.

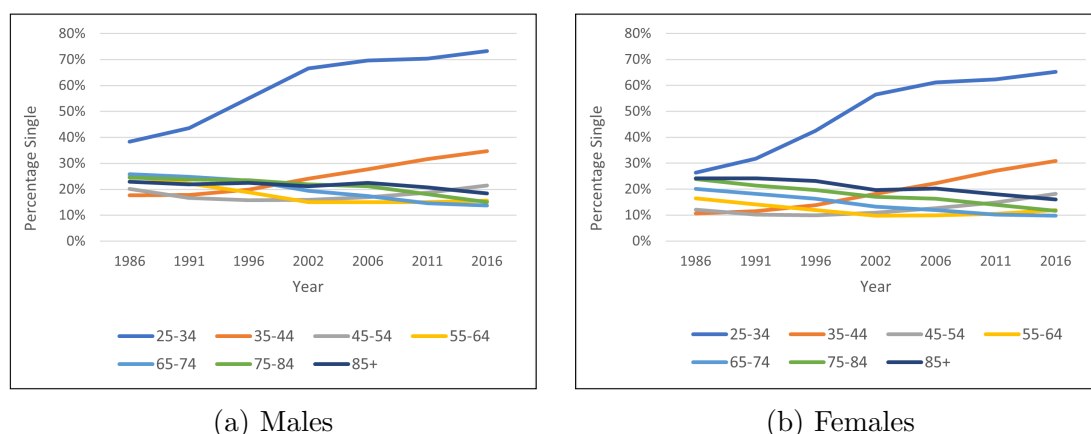


Figure 3.22: Percentage of males and females single in Ireland from 1986 – 2016 by age group.

Figure 3.23 presents the EWMI for individuals aged 65 and older, shown by marital status (single, married, and other). Data spans two years for both males and females (2015/16 and 2016/17). As can be seen, single people experience higher EWM compared to married people for both males and females. Changing living patterns in the future could impact on seasonal mortality trends.

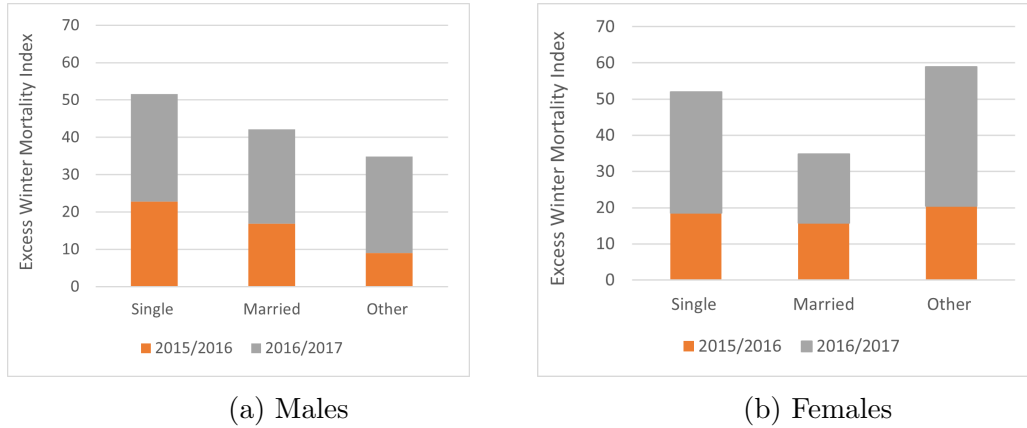


Figure 3.23: EWMI for those aged 65+ for the years 2015/16 and 2016/17 for males and females respectively.

3.7 Discussion

This chapter analysed seasonal mortality trends at older ages in Ireland over the period 1986 to 2017. During this time, a general decline in EWM was observed across both genders especially for those aged 60-69 and 70-79. Furthermore, mortality improvements during this period were higher during the winter months compared to summer but were also more volatile. In general, males consistently experienced greater reductions in mortality rates than females in both the summer and winter seasons over the period. Improvements in winter mortality peaked around the turn of the century, a trend that likely reflects the broader context of Ireland's rapid economic growth during that time, which was accompanied by substantial increases in public health expenditure (see Appendix 3). In contrast, gains during the summer months peaked slightly later and were comparatively smaller. The chapter also analysed the potential impact of seasonality on future mortality projections by considering an increased seasonal mortality gap, a reduced seasonal mortality gap and no change in the seasonal mortality gap in 2040 relative to the baseline period 2015-2017.

The analysis in this chapter also highlighted that EWM is generally higher at older ages for shared accommodations such as nursing homes and community hos-

pitals. Changes in the proportion of older adults residing in institutional care, or shifts in the age at which such transitions occur, are therefore likely to shape future patterns in seasonal mortality.

Variation in EWM was also varied by marital status. Single males exhibited the highest levels of EWM, whereas for females, those in the ‘other’ marital status category (such as widowed or separated) were most affected.

While traditionally overlooked in actuarial modelling, the risks associated with seasonal and excess winter mortality contribute to mortality and longevity risk for insurers and pension providers and should be considered when setting mortality assumptions for actuarial applications, particularly at older ages. As discussed by Hall and Naqvi (2019) seasonal differences in mortality between and within populations are a source of demographic basis risk while seasonal mortality trends influence projections of future mortality and are a source of trend risk. In 2019 the UK insurance regulator, in a letter to all chief actuaries, highlighted the importance of reflecting worsening excess winter mortality trends in mortality improvements and projections (Malik (2019)). As discussed by Madaniyazi et al. (2024) climate change could significantly impact on seasonal mortality variations in the future. In the UK, the Prudential Regulation Authority (PRA) has issued supervisory guidance that explicitly requires insurers and actuaries to incorporate climate-related risks when setting mortality assumptions (PRA (2019) and PRA (2025)). Similarly, in Ireland, the Central Bank has set supervisory expectations for insurance firms to embed climate change risks in their governance and mortality assumptions (Central Bank of Ireland (2021)). Consideration of the impact of climate risk on mortality assumptions in Ireland and the UK should include assessing the impact of climate change on seasonal variations in future mortality.

Both the Irish and UK governments have recognised the public health risks associated with excess winter deaths and have implemented targeted policy interventions. In Ireland, the government operates the Fuel Allowance Scheme, offering weekly heating support during the winter to low-income households (CitizensIn-

formation (2024)) and the Warmer Homes Scheme provides free energy efficiency upgrades to eligible homes, aiming to reduce heating costs and improve indoor thermal comfort (SEAI (2025)). In the UK, the Cold Weather Plan for England was launched in 2011 to increase public and institutional preparedness during cold spells, aiming to minimise the health impacts of cold weather (UK Health Security Agency (2022)). The Warm Home Discount Scheme, also introduced in 2011, provides electricity bill rebates to low-income households at risk of fuel poverty (Ofgem (2022)). The National Institute for Health and Care Excellence (NICE) issued public health guidance in 2015 on improving outcomes for people vulnerable to the cold, with a focus on housing conditions and inter-agency coordination (NICE (2015)). These initiatives collectively aim to reduce seasonal mortality risks, particularly among elderly and vulnerable populations.

The findings in this chapter highlight the importance of seasonal mortality in Ireland and emphasise the need to consider demographic and policy factors, as these are closely linked to EWM and play an important role in improving mortality outcomes. As the Irish population continues to age, targeted government interventions will be essential in mitigating seasonal mortality risks and ensuring equitable health outcomes for the older population in Ireland.

Appendix 3.1: Health Spending during the Celtic Tiger Era

Health expenditure in Ireland has fluctuated over the past 30 years reflecting changes in the economic climate. Figure 3.24 present the level of public health expenditure in Ireland from 1990-2016. Spending contracted during the recession years but increased in boom years. From 1997, expenditure increased considerably reaching a peak in 2009 and then falling as a result of the economic downturn. In more recent years, total health spend has increased significantly reaching record levels in 2018 of €16.5bn (CSO (2024)). As evident from Figure 3.24, public health expenditure particularly increased significantly during the Celtic Tiger era (c.1997-2007) and interestingly, mortality improvements were also highest during this period (see Figure 3.1).

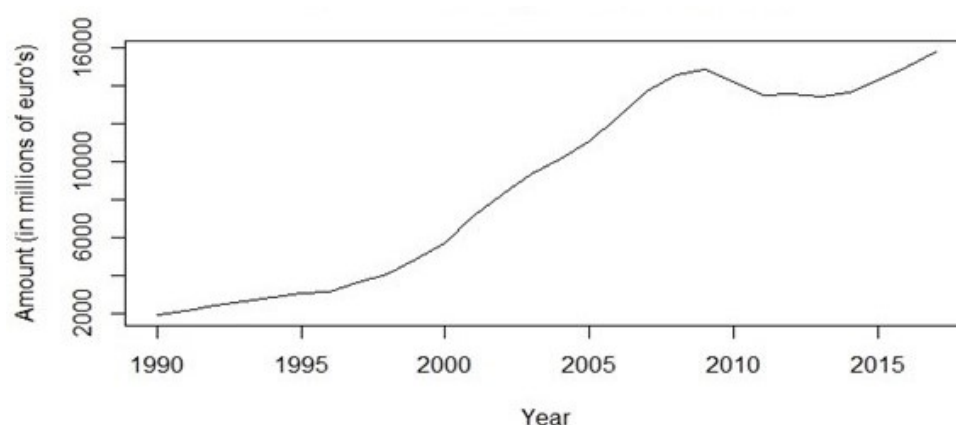


Figure 3.24: Public Health Expenditure in Ireland over the period 1990 – 2016. [Data Source (CSO (2015), NISRA (2025b), and CSO (2024))]

Chapter 4

Excess Mortality in Ireland during the Covid-19 pandemic

4.1 Background

The Covid-19 pandemic, caused by the SARS-CoV-2 virus, emerged in December 2019 in Wuhan, China (Al-Rohaimi and Al Otaibi (2020)) and rapidly spread around the world. On 30th January 2020, the World Health Organisation(WHO) declared the outbreak a Public Health Emergency of International Concern and by 11th March 2020, it was officially classified as a global pandemic (WHO (2020)). As of April 2024, approximately 7 million confirmed deaths have been reported worldwide due to Covid-19 (Worldometer (2024)) with other research estimating the actual death toll may be significantly higher. A study published in The Lancet (2022) estimated around 18.2 million excess deaths globally between 2020 and 2021 while the WHO estimated around 14.9 million excess deaths during the same period (WHO (2022)). These latest studies reflect the broader impact of the pandemic including under-reported deaths and indirect effects.

Ireland's first confirmed case occurred on 29th February 2020, when an individual, having returned from Italy, tested positive for the virus (BBC (2020)). As cases and hospitalisations increased the Irish government promptly implemented restrictions, including school closures and a nationwide lockdowns in March 2020 (HPSC

(2021)). The initial wave peaked in April 2020, but as restrictions were relaxed over the summer, a resurgence in cases led to the imposition of stricter measures again in the autumn. This second wave, which began in September 2020 (HPSC (2021)), was worsened by the onset of winter and increased indoor social interactions. The third and most severe wave hit in late 2020 and early 2021, driven by more transmissible variants of the virus, which significantly impacted public health (Kelly et al. (2022), Cazelles et al. (2021), HPSC (2021), and HPSC (2020)). Vulnerable populations, including the elderly and those with pre-existing health conditions, were disproportionately affected by the virus (Liu, Dean, and Elder (2023) and Loughrey et al. (2023)).

In addition to restrictions and lockdowns, Ireland launched a vaccination campaign on 29th December 2020 (HPSC (2021)). The vaccination program initially prioritised healthcare workers and those in long-term care, before expanding to the general population throughout 2021. As of 08th November 2021, the vaccination uptake among individuals aged 12+ in Ireland had reached 90.5% and Ireland held the highest vaccination rate in the EU (Griffin (2021)). The success of the vaccination program in Ireland played a key role in shifting the trajectory of the pandemic, allowing for a gradual easing of restrictions.

According to the WHO, the Covid-19 pandemic officially ended on 05th May 2023 (Sarker et al. (2023)). Ireland like many other countries, had already started easing restrictions and transitioning to a post-pandemic phase earlier. However, the ongoing treatment of Covid-19 as an endemic disease requires continued public health surveillance (McDonald (2023) and Contreras, Iftekhhar, and Priesemann (2023)).

Ireland is currently undertaking a formal Covid-19 evaluation of its response to the Covid-19 pandemic, with the final report expected by mid-2026 (Medical Independent (2025)). This report is expected to provide valuable insights into the country's pandemic management strategies. It will also contribute to the development of future public health policies aimed at mitigating the impact of future pandemics.

Emerging research indicates an increased risk of future pandemics, largely influenced by environmental factors (Ferreira, Doursout, and Balingit (2023), Casadevall et al. (2024), He et al. (2023), Gorji and Gorji (2021), and Carlson, Albery, Eskew, et al. (2024)). Climate change is altering ecosystems and will therefore increase human-wildlife interactions facilitating the emergence and transmission of novel diseases. (Abrahms et al. (2023)). Furthermore, shifting weather patterns and the rise in extreme weather events is creating conditions that support the spread of infectious diseases (Epstein (2001)). When combined with globalisation, these factors increase the risk of rapidly spreading new infectious diseases.

This chapter examines the mortality impact of the Covid-19 pandemic in Ireland and sets out the methodology for integrating the experiences of the pandemic years into the official National Labour & Population projections (2023-2057). The chapter is structured as follows:

- **Section 4.2** presents a published paper, for which I was the lead author on the level of excess mortality in Ireland during the Covid-19 pandemic. This paper is published on the Society of Actuaries in Ireland website (Daly et al. (2024)).
- **Section 4.3** provides further insights into the methodological approaches used in the published paper described in Section 4.2.
- **Section 4.4** outlines the development of the official National Labour & Population projections (2023-2057) for Ireland, for which I co-led the mortality analysis in collaboration with Professor Shane Whelan from University College Dublin (Whelan et al. (2024)).

4.2 Paper: Excess Mortality in Ireland during the Covid-19 pandemic

Executive Summary

This report examines the level of excess all-cause mortality experienced in Ireland during the Covid 19 pandemic, offering some insights beyond the tally of reported Covid-19 fatalities. Focusing specifically on the first two years of the pandemic, 2020 and 2021, it examines excess deaths as a metric in understanding the pandemic's impact.

Excess mortality is defined as the difference between observed deaths and expected deaths. It is important to note that there is not one definitive approach to calculating excess mortality – mainly because, whilst observed deaths will ultimately be a matter of record (i.e. they are objective), the calculation of expected deaths is dependent on the choice of methodology (i.e. it relies on professional judgement). This analysis is based on a methodology that relies on past experience as a benchmark for expected deaths. As presented in this report, different past periods for estimating expected deaths result in varying levels of excess mortality.

A common approach during the Covid-19 pandemic, which allowed for timely estimates of excess mortality, was to calculate expected deaths as the average of the annual deaths in a preceding number of years. However, this methodology is subject to distortion in times of rapid population changes (e.g. population growth, population aging, mortality improvements). As set out in sections 1 and 2, the Irish population was subject to such changes in the relevant years, and this should be reflected in the calculation of excess mortality during the pandemic. A more appropriate methodology, which allows for these population changes, is to base the excess mortality calculation on Age Standardised Deaths. This approach is described in detail in section 4.2.3. In summary, it takes the actual deaths by age for each year, and re proportions them to reflect what they would be if the population had

the same size and age distribution every year. In this manner, the distorting effect of changes in population is removed.

The benchmark period chosen in this study is based on the three years preceding the pandemic (2017-2019). As discussed in the report, this period is selected due to its proximity to the pandemic years and its representation of pre-pandemic mortality trends, providing a relevant basis for estimating expected deaths in 2020 and 2021. The deaths were standardised to the population size and mix of 2021.

Under this methodology, the analysis reveals broadly no excess mortality in 2020, indicating relatively stable mortality compared to the pre-pandemic years of 2017-2019. However, 2021 witnessed an increase in excess mortality, signalling a more significant impact on mortality patterns during the pandemic's second year. Cumulatively, Ireland experienced c.1,100 excess deaths during the pandemic years of 2020 and 2021. That figure underscores the toll imposed by the pandemic on the nation's population and such insights are important for understanding the broader mortality implications of the pandemic beyond reported Covid-19 fatalities.

A reader observing the significant downward trend in mortality from 2010-2019 (see Figure 4.3), might reasonably expect that, in the absence of Covid-19, the trend would have continued into 2020-2021 resulting in lower expected deaths and hence a higher number of excess deaths or higher excess mortality. However as stated above, we opted to calculate the expected mortality for 2020 and 2021 by using the average observed mortality from 2017 to 2019. This method is objective as it relies on actual recorded data from those years.

4.2.1 Introduction

Ireland has experienced significant improvements in mortality since the start of the 21st century with total life expectancy at birth increasing by over six years between 2000 and 2019 (Eurostat 2024). However, these rapid mortality improvements were brought to an abrupt halt by the onset of the SARS-Cov-2 (Severe Acute Respiratory Syndrome Coronavirus 2), commonly referred to as Covid-19, pandemic in early

2020. This chapter investigates the impact of the Covid-19 pandemic on mortality in Ireland in 2020 and 2021 and builds on previous work carried out by the Society of Actuaries Covid-19 Action Group (SAI (2021)).

According to research by the World Health Organisation (WHO) Covid-19 resulted in an estimated 14.9 million excess deaths worldwide in 2020 and 2021 (WHO (2022)). Recent research on the impact of Covid-19 on mortality in Ireland has been contradictory. For example, a report by the OECD (OECD (2023)) indicated that Ireland did not experience excess mortality during the pandemic years 2020-2022. In contrast, analysis by the Central Statistics Office (CSO) (CSO (2022)) indicated 3,533 excess deaths in Ireland over the period 2020-2021. In both these cases, the research was based on different data sources (provisional CSO data for the OECD report and data from the website RIP.ie for the CSO analysis which was completed in advance of the alternative data becoming available), covered different time periods and employed different methods for calculating excess mortality. Research on the impact of Covid-19 on mortality in Ireland has been hampered by the delay in obtaining timely, official statistics on Irish mortality during the pandemic (CSO (2020)). The delay in obtaining official mortality statistics for 2021 was further exacerbated by the impact of the HSE cyber-attack in May 2021 on death registrations. Finalised death data for Ireland for 2021 was made available by the CSO towards the end of 2023 and is used in our analysis.

Analysis of all-cause excess mortality is the most common approach for assessing the impact of the Covid-19 pandemic on mortality and allows assessment of both the direct and indirect effects (e.g. reduced access to healthcare, reduction in traffic accidents) of the pandemic on mortality. Excess mortality is calculated by comparing the observed number of deaths during the pandemic with the number of deaths that would have been expected to occur in the absence of the pandemic. The expected number of deaths is based on the deaths which occurred over a similar, benchmark or baseline period, immediately prior to the pandemic. Therefore, the accuracy of the excess mortality calculations is dependent on the appropriateness of the chosen

benchmark period and the consideration of any potential adjustments needed to account for changes in population size and demographics over time.

The choice of the benchmark period requires careful consideration to ensure that the resulting mortality figures accurately reflect the underlying trends and patterns in the population. This report considers three benchmark periods for calculating excess mortality in 2020 and 2021 during the Covid 19 pandemic – the 3-year period 2017-2019, the 5-year period 2015-2019 and the 10-year period 2010-2019. Excess mortality is calculated for males and females combined in the main body of the report while results by gender are presented in the Appendix 4.2.1.

The report is organised as follows: Section 4.2.2 discusses the data used in the analysis, Section 4.2.3 describes the approach used to determine excess mortality for 2020 and 2021 and presents the results, while Section 4.2.4 concludes with a brief discussion of the results. Appendix 4.2.2 examines the variability inherent on the methodology assumed in this report.

4.2.2 Data

Death and population data for the pandemic years 2020 and 2021 was obtained from the Central Statistics Office (CSO) Ireland aligning with the data provided on the CSO website as of March 2024. As the death data for 2022 had not been finalised when this report was written, this analysis solely focuses on excess mortality in the years 2020 and 2021. Additionally, to establish an appropriate benchmark period for evaluating the extent of excess mortality during the Covid-19 pandemic, it was necessary to obtain death and population data for the 10-year period preceding the pandemic (2010-2019) which was also sourced from the CSO.

Data on the number of deaths split by gender, year (2010-2021) and by single year of age to age 98 and for ages 98+ combined were provided. The death data is based on the date of occurrence and is finalised data. Corresponding population estimates were also provided. The CSO calculates annual population estimates by projecting forward the relevant census population and subtracting vital events

and migration flows. The annual population figures for 2017-2021 were revised by the CSO from previous estimates following a detailed analysis of the 2022 census results. The annual population estimates have an effective date of the 1st April and are assumed to approximate mid-year population estimates.

Figures 4.1 and 4.2 present the annual number of deaths and population estimates respectively for ages 0-64 and 65+ over the period 2010-2021. From Figure 4.1 we can see that there was little change in the number of deaths aged 0-64 over the period 2010-2021. In contrast, the number of deaths over age 65 shows a gradual rise during the period from 2010 to 2019, with more notable increases observed in 2020 and 2021. Figure 4.2 shows a gradual increase in the overall population from 2010 to 2015, amounting to a 2.9% rise over this 5-year period. However, a more substantial increase occurred after 2015. Specifically, the overall population witnessed a c.7% growth (around 342,000 individuals) over the 5-year period 2015-2020.

Breaking the population growth down by age group showed that, over the 5-year period 2015-2020, the population aged 0-64 increased by approximately 6% while the population aged 65+ increased by approximately 19%. Furthermore, during the pandemic (from 2020 to 2021), there was a 2.9% increase in the population aged 65+. Additionally, while not shown in the graphs we noted that the population aged 85+ increased by approximately 16% over the period 2015-2020 with a further increase of 2.6% from 2020-2021. This rapid increase in the population aged 85+ added to the challenges posed by the Covid-19 pandemic, as the Covid-19 virus disproportionately impacted older individuals compared to their younger counterparts (Williamson et al. (2020)).

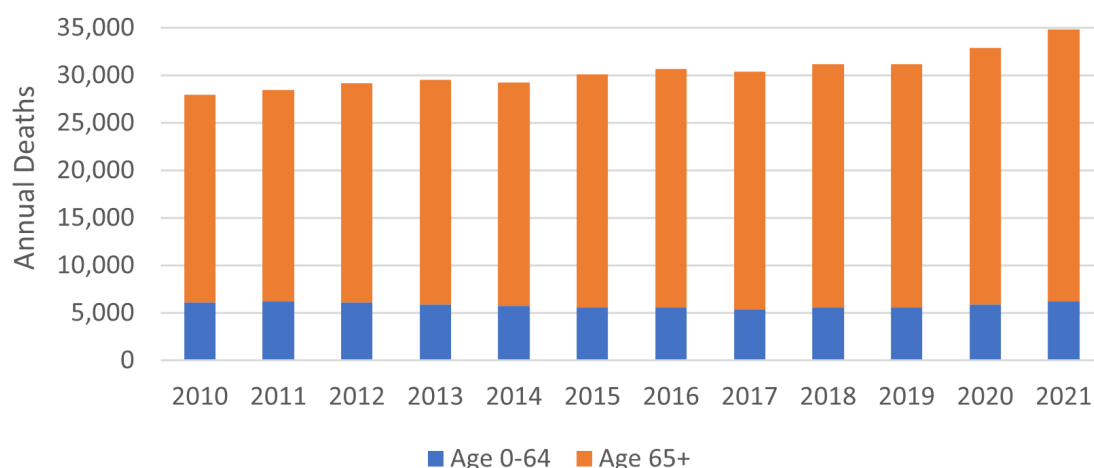


Figure 4.1: Number Of Deaths for age group 0-64 and 65+ over the period 2010-2021.

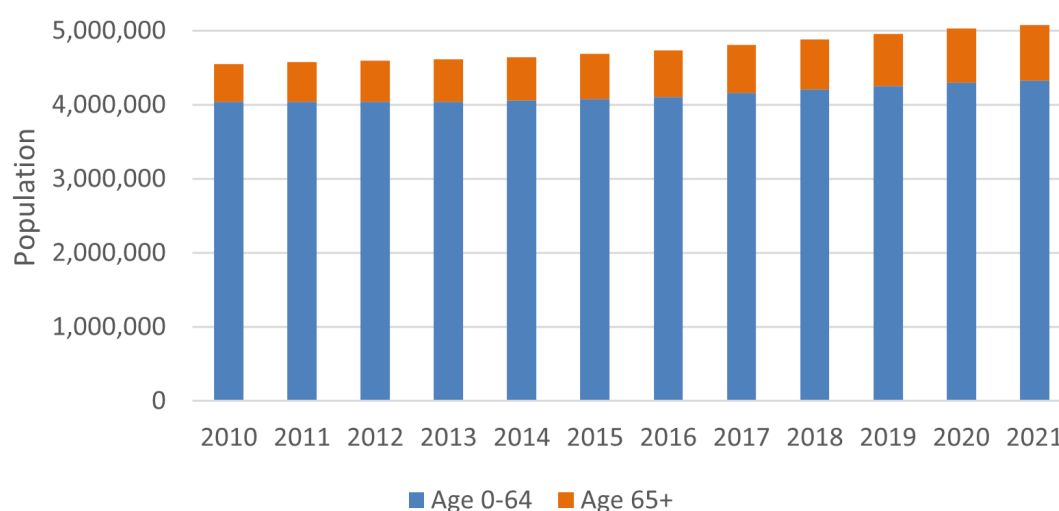


Figure 4.2: Population for age group 0-64 and 65+ over the period 2010-2021.

4.2.3 Age Standardised Excess Deaths in 2020 and 2021

To allow for changes in the age structure of the population over time it is necessary to standardise the annual deaths prior to calculating the excess mortality (Centers for Disease Control and Prevention (CDC) (1995)). Age Standardised Mortality Rates (ASMRs) allow for mortality comparisons between populations with different age structures and the standardised deaths were calculated based on ASMRs by single year of age to age 94 and for ages 95+ combined, standardised relative to

the 2021 population for Ireland. The resulting standardised deaths for each year reflect the deaths that would have occurred in each year if the population in that year matched the population in 2021 (the standard population).

Figure 4.3 presents the trend in the standardised deaths over the period 2010-2021. In general, the standardised deaths declined over the pre-pandemic period 2010-2019 (indicating mortality improvement over the period) though the rate of decline varied over time. The 3-year benchmark period 2017-2019 experienced an annualised decline in standardised deaths of approximately 2.5% per annum compared to annualised declines of only 1.7% per annum for the 5-year benchmark period 2015-2019 and 1.6% per annum for the 10-year benchmark period 2010-2019. The standardised deaths for 2020 and 2021 show consecutive increases compared to the 10-year low observed in 2019.

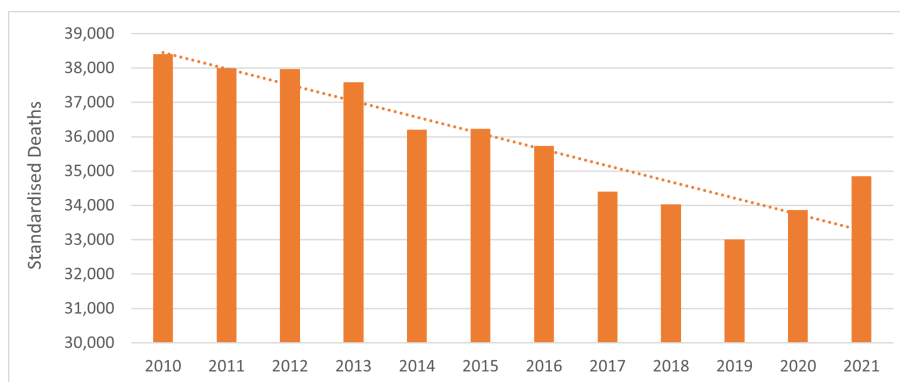


Figure 4.3: Standardised deaths for the period 2010-2021 - standardised relative to the 2021 population.

Benchmark	Time Period	Average Annual Standardised Deaths
Benchmark 1	2017-2019	33,818
Benchmark 2	2015-2019	34,684
Benchmark 3	2010-2019	36,158

Table 4.1: Average Annual Standardised Deaths for the benchmark periods listed.

Figure 4.4 compares the standardised deaths experienced in 2020 and 2021 with the average annual standardised deaths for the 3-year, 5-year, and 10-year benchmarks. For 2020, the standardised deaths fall below the 5-year and 10-year benchmarks while broadly aligning with the 3-year benchmark. This suggests little or no

excess deaths occurred in 2020 under any benchmark. However, in 2021, the standardised deaths significantly surpass the 3-year benchmark, fall below the 10-year benchmark, and marginally exceeds the 5-year benchmark. This indicates a nuanced situation for 2021, no excess deaths are observed when using a 10-year benchmark, significant excess deaths are evident with a 3-year benchmark, and marginal excess deaths are observed when using a 5-year benchmark. Therefore, it is apparent that the choice of benchmark period significantly influences the level of excess mortality during the Covid-19 pandemic.

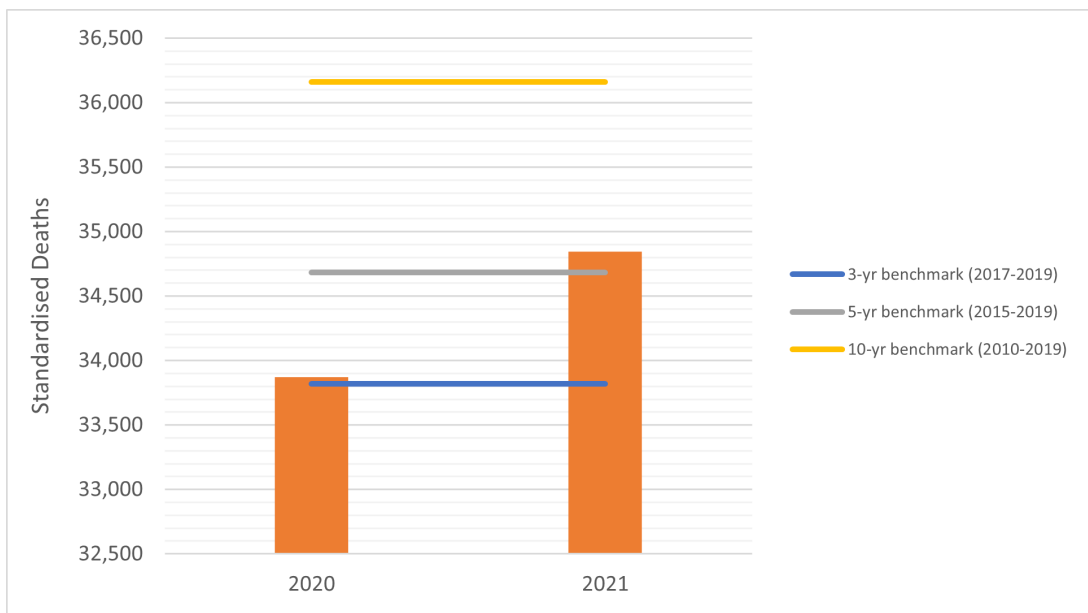


Figure 4.4: Comparison of the standardised deaths for 2020 and 2021 with those of the benchmark period shown.

All else being equal, in prediction exercises, the inclusion of more experience data (in this case, years) strengthens the statistical significance of a benchmark. However, the significant downward trend in mortality observed in the period 2010 to 2019, renders the earlier years less useful as a predictor of mortality in 2020 and 2021. We believe the 3-year benchmark from 2017 to 2019 represents a reasonable balance between volume of experience data and proximity to the Covid-19 pandemic. Consequently, all subsequent analyses are based on the 3-year benchmark period 2017-2019.

Table 4.2 presents the excess deaths for 2020 and 2021 as the difference between

the standardised deaths for 2020 and 2021 (the actual deaths) and the standardised deaths for the benchmark period 2017-2019 (the expected deaths). Under this approach, both 2020 and 2021 register an increase in excess mortality though the increase in 2020 is small. The results demonstrate that Ireland experienced approximately 1,100 excess deaths over the two-year period.

	Standardised Deaths	Average Annual Standardised Deaths for 2017–2019	Excess Deaths
2020	33,870	33,818	52
2021	34,844	33,818	1,026
Total Excess Deaths for 2020 + 2021			1,078

Table 4.2: Excess deaths in 2020 and 2021 (adjusted for population differences) relative to the benchmark period 2017–2019.

It should be noted that aside from the subjectivity in determining an appropriate benchmark period to use in calculating the expected deaths, there are further approximations in the calculation of excess deaths, due to, for example:

- annual mortality rates being subject to random fluctuations (partially due to the relatively small population size for Ireland)
- the aggregation of data beyond age 95
- the use of population estimates as opposed to actual population numbers.

It could be considered a more accurate approach to calculate the excess deaths in 2020 by using standardised deaths relative to the population for 2020. However, doing so resulted in only minor differences to the figures quoted above and did not affect the overall estimate of approximately 1,100 excess deaths for Ireland over the two-year period 2020 and 2021.

Age Standardised Excess Deaths by Age Group

The Covid-19 pandemic primarily impacted the elderly population, warranting a more thorough analysis of this demographic. Figure 4.5 presents the standardised deaths in 2020 and 2021 for the three age groups: 0-64, 65-84, and 85, relative to the corresponding average annual standardised deaths for the 3-year benchmark period 2017-2019. As can be seen, age groups 0-64 and 85 experienced excess mortality in both 2020 and 2021 while age group 65-84 only experienced excess mortality in 2021. The excess deaths in 2020 for ages 0-64 and 85, and in 2021 for ages 65-84, were relatively small and could be due to normal fluctuations. Furthermore, individuals aged 65-84 make up only a small proportion of the population (around 13% in 2021), making them particularly prone to random variations (see Appendix 4.2.2 for more information).

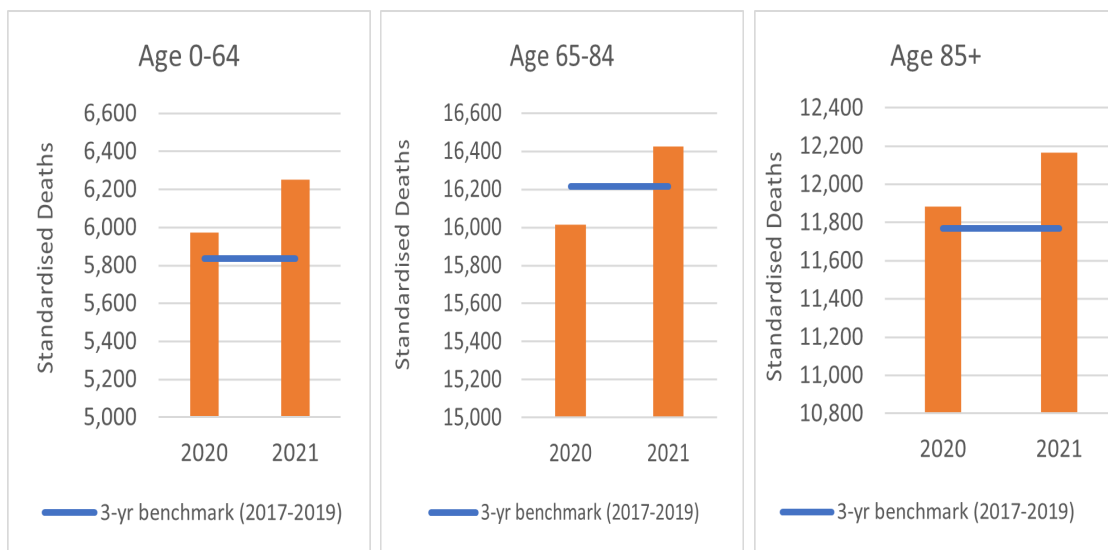


Figure 4.5: Comparison of the standardised deaths by age group for 2020 and 2021 with those of the benchmark periods shown.

Table 4.3 presents the excess deaths for each age group in 2020 and 2021. The excess deaths are calculated using the method described in the preceding section. As expected, individuals aged 85+ had the highest excess deaths as a percentage of population (0.147% and 0.512%) for both 2020 and 2021, despite individuals aged 0-64 having the highest absolute number of excess deaths (137 and 418) in those respective years.

Year	Excess Deaths				Excess Deaths expressed as a % of the 2021 population per specific age group			
	0–64	65–84	85+	All Ages	0–64	65–84	85+	All Ages
2020	137	-199	114	52	0.003%	-0.030%	0.147%	0.001%
2021	418	211	397	1,026	0.010%	0.031%	0.512%	0.020%

Table 4.3: Excess deaths in 2020 and 2021 (adjusted for population differences) by age group relative to the benchmark period 2017–2019.

4.2.4 Conclusion

The results presented in Section 4.2.3 (and onwards) show that excess deaths in Ireland during the Covid-19 pandemic were higher in 2021 compared to 2020. Among various potential contributing factors to the lower excess death in 2020, government-imposed restrictions stand out as one significant potential factor. The Oxford Coronavirus Government Response Tracker (OxCGRT) conducted an evaluation of stringency indices for numerous countries amidst the Covid-19 pandemic. This index amalgamated nine response metrics, encompassing factors such as school closures and stay-at-home directives (Mathieu et al. (2020)). Furthermore, it was weighted according to the percentage of vaccinated individuals within each population. This daily-calculated index represents the average score of the nine metrics, each graded on a scale from 0 to 100. A higher score signifies a more rigorous response, with 100 denoting the most stringent level of measures implemented.

Figure 4.6 presents the stringency index for Ireland throughout 2020 and 2021. As depicted in the graph, the index was set to zero during January and February 2020, reflecting the absence of restrictions until 12 March 2020. From 12 March to 31 December (the overlapping periods of the 2020 and 2021 index), it is evident that significantly stricter measures were implemented in 2020 compared to 2021. This underscores the effectiveness of the stringent Covid-19 restrictions employed in 2020 in containing deaths.

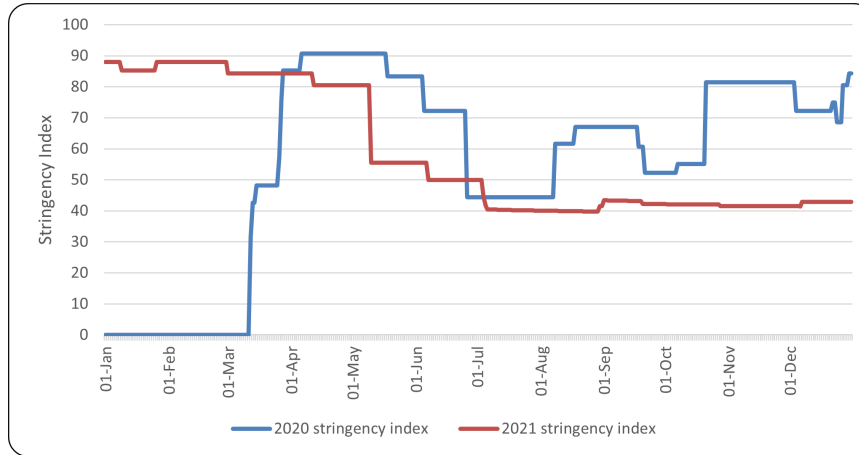


Figure 4.6: Stringency Index values for 2020 and 2021 for Ireland.

However, evaluating how well a particular country managed the pandemic involves far more complex factors than simply assessing the stringency of its lockdown measures. For example, broader issues such as population density plays an important role, as highly concentrated urban areas can facilitate faster virus transmission regardless of restrictions (Rocklöv and Sjödin (2020)). Climate conditions may also impact the virus’s spread (Sajadi et al. (2020)) and population compliance with health guidelines, including mask-wearing and social distancing, considerably influences outcomes (Bavel et al. (2020)). Other interventions, such as the speed and efficiency of testing, contact tracing, healthcare capacity and public communication strategies, are equally important in understanding a country’s overall pandemic response. Therefore, any evaluation of pandemic effectiveness should reflect the complexity of multiple influences rather than lockdown measures alone.

In conclusion, this analysis reveals a contrast in Ireland’s mortality trends between 2020 and 2021 when assessed against the 3-year benchmark period immediately prior to the pandemic. For all ages combined excess deaths were observed in 2021 while only marginal excess deaths were observed in 2020. As expected, the oldest age group (aged 85) experienced the highest proportional excess mortality in both years. Notably, we based our assessment on the 3-year benchmark period of 2017-2019 which we deemed to be the most appropriate benchmark due to significant mortality improvements experienced during this period. The absence of

excess deaths indicated by the 5 and 10-year benchmarks could be attributed to these benchmarks not fully reflecting the recent mortality advancements preceding the pandemic.

It is important to note however, that this analysis does not attempt to estimate what expected deaths might have been in 2020 and 2021 had the significant downward trend in mortality rates observed in the period 2010-2019 continued. It is reasonable to assume that such an exercise would indicate that the pandemic did result in higher than expected deaths in 2020 and a more significant impact in 2021 than suggested by the methodology outlined in Section 4.2.3. Thus, it is crucial to carefully evaluate and consider the methods used when interpreting death trends and excess deaths during the Covid-19 pandemic.

Covid-19 is expected to become endemic in the population and the long-term impact of Covid-19 on future mortality is uncertain. The negative effects of delayed medical diagnoses and treatment during the pandemic and the impact of post Covid conditions (e.g. long Covid) on mortality will emerge slowly. In contrast, factors such as improved vaccine effectiveness, greater public health awareness and an increased focus on monitoring and improving care for the elderly could positively impact on future mortality trends.

Appendix 4.2.1: Gender Specific Excess Mortality

Figures 4.7 and 4.8 present the trends in the standardised deaths for males and females respectively for the period 2010-2021.

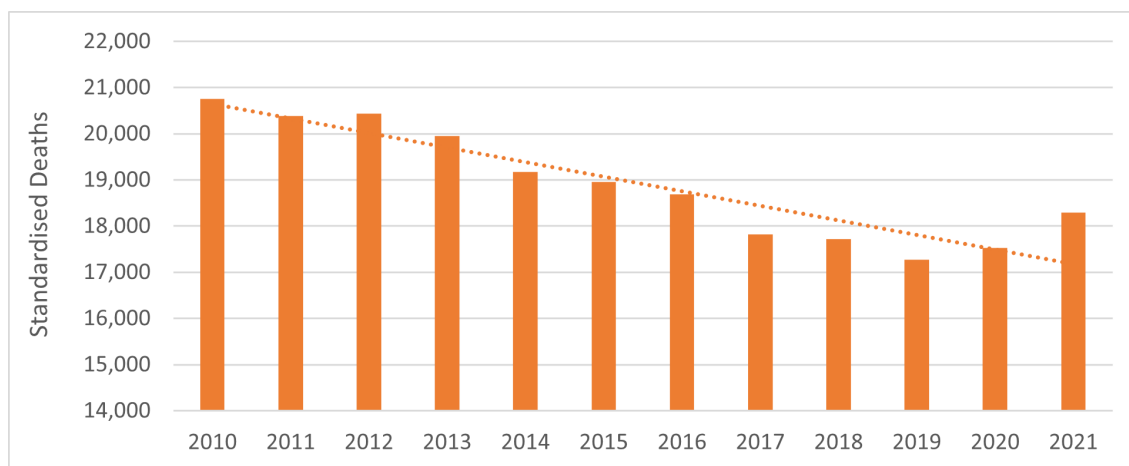


Figure 4.7: Standardised deaths for males for the period 2010-2021 – standardised relative to the 2021 male population.

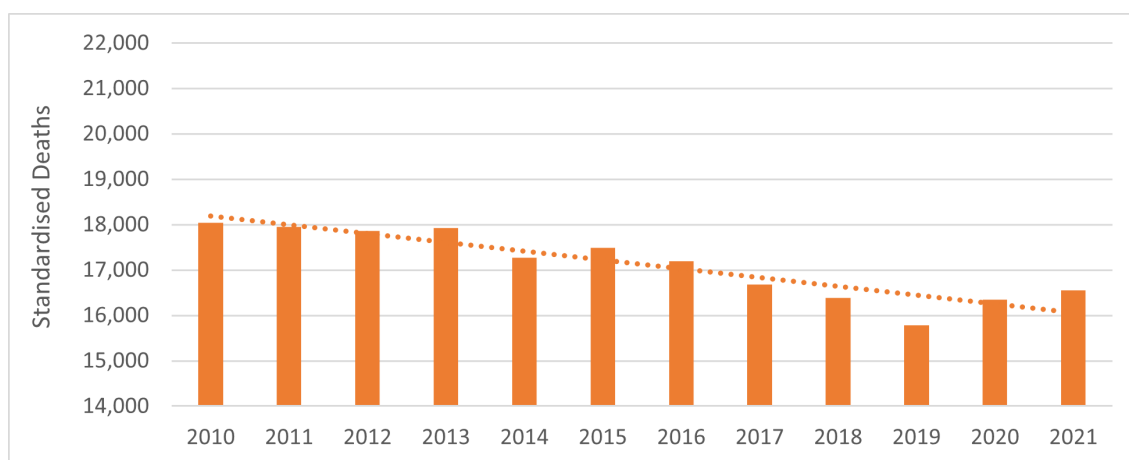


Figure 4.8: Standardised deaths for females for the period 2010-2021 – standardised relative to the 2021 female population.

Tables 4.4 and 4.5 present the excess deaths for 2020 and 2021 for males and females respectively. As before, the excess deaths are calculated as the difference between the standardised deaths for 2020 and 2021 (the actual deaths) and the standardised deaths for the benchmark period 2017-2019 (the expected deaths). Please note that the total excess deaths for males and females as shown in Table 4.4

and Table 4.5 do not match the total presented in Table 4.2 due to the averaging implied by using a combined population for males and females relative to the gender specific populations used in Tables 4.4 and 4.5.

	Standardised Deaths	Average Annual Male Standardised Deaths for 2017–2019	Excess Deaths
2020	17,533	17,602	-69
2021	18,296	17,602	694
Total Excess Deaths for 2020 + 2021			625

Table 4.4: Excess male deaths in 2020 and 2021 (adjusted for population differences) relative to the benchmark period 2017–2019.

	Standardised Deaths	Average Annual Female Standardised Deaths for 2017–2019	Excess Deaths
2020	16,351	16,282	69
2021	16,548	16,282	266
Total Excess Deaths for 2020 + 2021			335

Table 4.5: Excess female deaths in 2020 and 2021 (adjusted for population differences) relative to the benchmark period 2017–2019.

Appendix 4.2.2: Understanding Variability

The variability of a country's death tolls naturally fluctuates from year to year. Figure 4.3 indicates that although mortality rates have generally improved over the past two decades, they haven't followed a consistent linear trend - for example, standardised deaths for the combined population slightly increased in 2015 compared to the preceding year, 2014. This prompts consideration: Could the excess deaths reported earlier in this chapter be due to normal fluctuations rather than solely attributed to the Covid-19 pandemic?

As an initial exploratory analysis to investigate whether such deviations could indeed be attributed to normal year-to-year fluctuations, Figure 4.9 models the relationship between year and standardised deaths from 2010 to 2019, assuming a broadly linear trend over time. A fitted trend line and accompanying 95% prediction interval (shaded band) illustrate the expected range for future values if this trend were to persist. Predicted deaths for 2020 and 2021 (shown as red dots) are compared with the actual observed deaths (black triangles). The results show that the 2020 figure falls within the predicted range while the 2021 value significantly exceeds the upper bound of the prediction interval. This conclusion is supported by Table 4.6, which shows a non-significant p-value for 2020 and a statistically significant one for 2021.

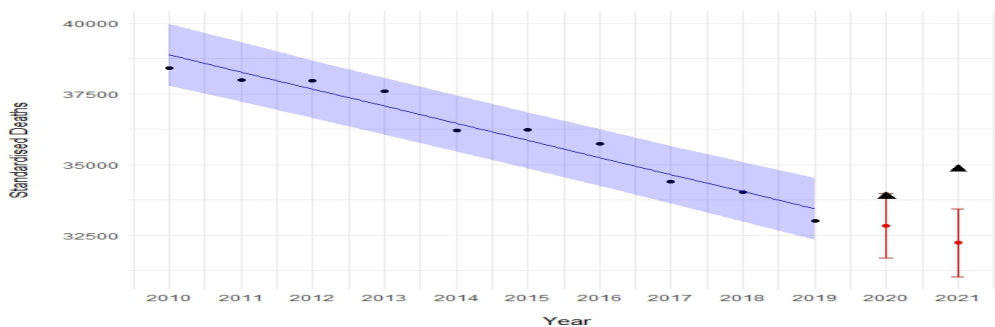


Figure 4.9: Comparison of actual and predicted standardised deaths (from simple linear model) for 2020 and 2021 along with the 95% upper and lower prediction intervals.

Year	Actual Deaths	Predicted Deaths	Prediction SE	P-Value
2020	33,871	32,838	494	0.070
2021	34,844	32,234	518	0.001

Table 4.6: Comparison of Actual vs Predicted Deaths (using simple linear model) for 2020 and 2021

Figure 4.10 shows the standardised deaths in 2020 and 2021 for all ages, along with expected deaths based on a 3-year benchmark (2017-2019) assuming the mortality rates remained constant over the period. It also includes dashed lines representing the 95% upper and lower confidence intervals calculated assuming deaths follow a Poisson distribution as per Appendix 3.3 of CMI working paper 97(CMI (2017)). The marginal level of excess deaths estimated for 2020 fall within this interval, indicating they lie within the realm of normal variability. However, in 2021, the excess deaths surpass the upper confidence interval, indicating that the elevated death toll in 2021 cannot be attributed to typical fluctuations but rather indicates a genuine increase in mortality under the stated methodology employed in this chapter.

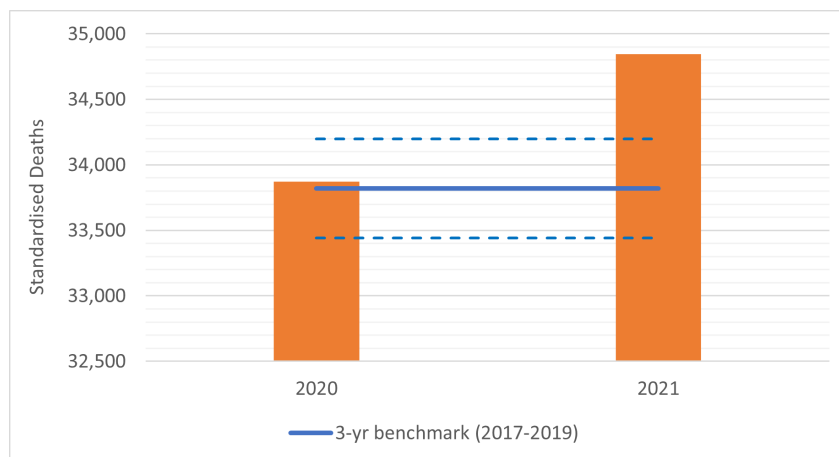


Figure 4.10: Comparison of the standardised deaths for the years 2000-2021 for all ages along with the corresponding 3-year benchmark and 95% upper and lower confidence intervals.

Figure 4.11 shows the standardised deaths in 2020 and 2021 by age group, along with expected deaths based on a 3-year benchmark. Again, it includes dashed lines representing the 95% upper and lower confidence calculated similarly to those in Figure 4.10. The marginal level of excess deaths estimated for 2020 for all 3 age groups fall within this confidence interval, indicating they lie within the realm of normal variability. However, in 2021, the excess deaths surpass the upper confidence interval for age groups 0-64 and 85, indicating that the elevated death toll in 2021 cannot be attributed to typical fluctuations but rather again indicates a genuine increase in mortality. For those aged 65-84, while there were excess deaths in 2021, they fall within the confidence interval. This group make up a smaller proportion of the population (about 13% in 2021) and because they are a smaller group, their numbers can fluctuate more. So, any excess deaths in 2021 for this age group might just be due to this natural variation.

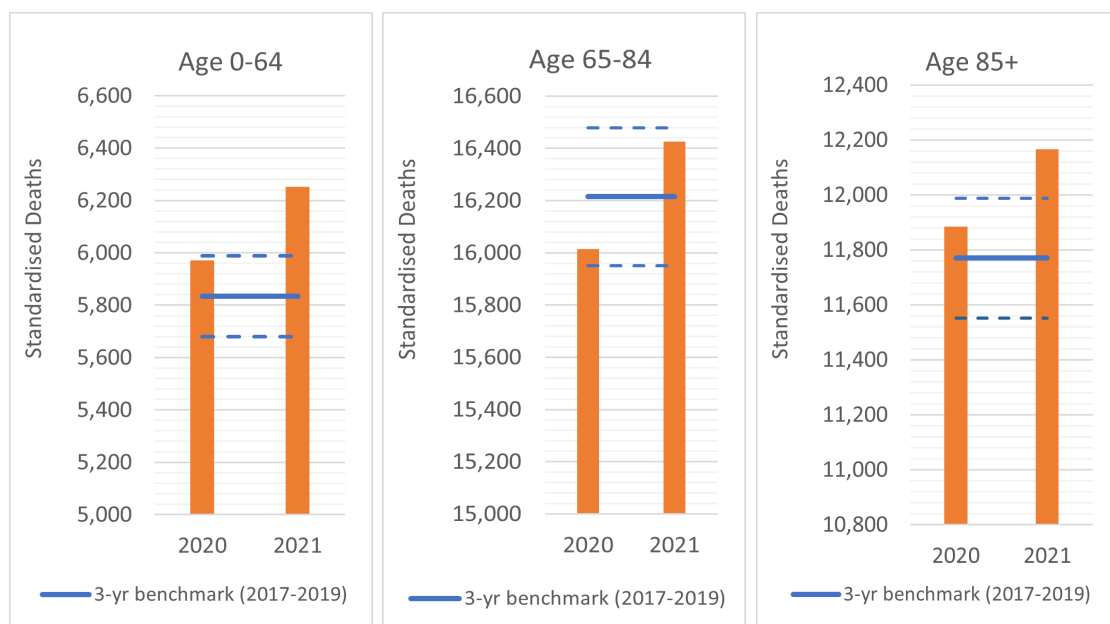


Figure 4.11: Comparison of the standardised deaths by age group for the years 2020 and 2021 with the corresponding 3-year benchmark and 95% upper and lower confidence intervals.

4.3 Additional insights on Excess Mortality during 2020 & 2021

This section provides further insights into the methodological approaches used in the published paper (Section 4.2), specifically the rationale for standardising deaths and the appropriateness of a 3-year benchmark period for Ireland.

4.3.1 Simple Excess Mortality in 2020 and 2021

A simple widely used method of assessing excess mortality is to compare the total number of deaths that occurred in the pandemic years of 2020 and 2021 with the average annual number of deaths which occurred over a pre-pandemic benchmark period (the expected deaths). Total deaths were 32,856 and 34,844 in 2020 and 2021 respectively. Table 4.7 compares the total deaths in the years 2020 and 2021 with the average annual deaths in the 3, 5 and 10-year benchmark periods prior to the pandemic. Under this approach, both 2020 and 2021, recorded excess deaths compared to all three benchmark periods. For comparison, the excess deaths are also expressed as a percentage of the expected deaths. The corresponding p-values for comparing the actual and expected deaths under the Binomial model in both 2020 and 2021, across all benchmark periods, were zero (correct to 16 decimal places).

		Actual Deaths		Excess Deaths		Excess Deaths as a % of Expected Deaths	
Period	Expected Deaths (Average Annual Deaths)	2020	2021	2020	2021	2020	2021
2017-2019	30,914	32,856	34,844	1,942	3,930	6.30%	12.70%
2015-2019	30,707	32,856	34,844	2,149	4,137	7.00%	13.50%
2010-2019	29,789	32,856	34,844	3,067	5,055	10.30%	17.00%

Table 4.7: Excess deaths in 2020 and 2021 (unadjusted for population differences) relative to the average annual deaths over the previous 3-year, 5-year and 10-year periods.

However, this analysis of comparing the death counts of the pandemic years with earlier years does not consider how the Irish population changed over this time and can misrepresent excess deaths for an aging population and/or a population that is growing over time. It is intuitive that as a population grows or ages, the number of deaths naturally rises, independent of any pandemic. Given the substantial shifts in both the composition and size of the Irish population between 2010 and 2021 but particularly over 2015-2021, the excess deaths analysis in the table above could be deemed inaccurate. Therefore as described in Section 4.2.3, an alternative measure of excess mortality, which accounts for changes in population structure by standardising the population, was used in the published paper.

4.3.2 Appropriateness of Benchmark period

Figure 4.12 presents a comparative analysis of standardised deaths over the 20-year period before the onset of the Covid-19 pandemic (2000-2019), along with the pandemic years of 2020 and 2021. The plot also includes the corresponding expected number of deaths for each year, referred to as the "3-year benchmark," derived from the average death rate in the preceding three-year period. All data points are standardised to the 2021 population, consistent with the methodology employed in the published paper. Examination of the plot reveals that standardised deaths for each year during the 20-year period before the pandemic never exceeded the preceding 3-year benchmark and therefore underscores the exceptional nature of the Covid-19 pandemic. This reinforces the methodology used in the published paper, namely, relying on the average death rate from the previous 3-year period to determine the expected number of deaths. This approach proves robust in identifying exceptional events such as the Covid-19 pandemic.

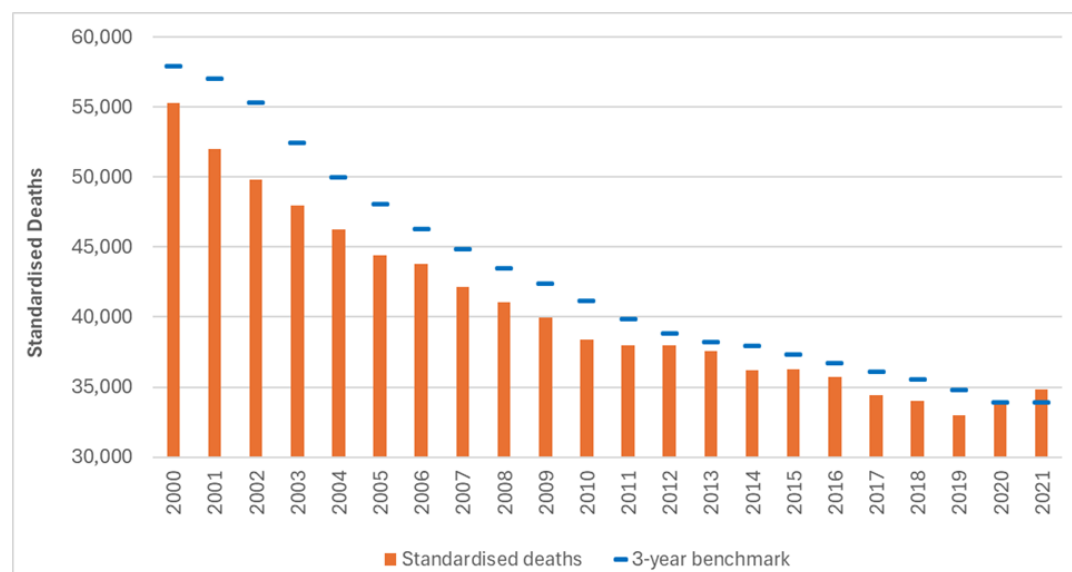


Figure 4.12: Comparison of the standardised deaths for the years 2000-2021 for all ages along with the corresponding 3-year benchmarks.

4.4 Population & Labour Force Projections for Ireland 2023-2057

4.4.1 Introduction

Official National Population & Labour force projections are essential, as they play a key role in informing key decisions made by a wide range of stakeholders, including governments, policymakers, businesses, and researchers. These projections are important for economic planning, optimising public service delivery, and guiding infrastructure development (Economic Co-operation and (OECD) (2012) and Bank (2020)).

In Ireland, Official National Population & Labour Force Projections are updated every five years, coinciding with the availability of data from the national census. These projections are developed by the CSO in collaboration with an expert group, which provides specialised knowledge on assumptions related to mortality, fertility, and migration (CSO (2024c)). The most recent projections span from 2023 to 2057 (CSO (2024c)). The mortality assumptions for the recent projections were established by a mortality sub-group, which was co-led by Professor Shane Whelan (UCD) and myself. While official National Population & Labour Force Projections are most influenced by the migration and fertility assumptions, the mortality expert group placed significant care on setting the mortality assumptions used in the projections due to their widespread application. For instance, alongside population projections, mortality assumptions are applied in several contexts including actuarial guidelines for calculating defined benefit (DB) pension scheme transfer values (SAI (2022)), other Actuarial Standards of Practice (ASPs), and government forecasts of housing demand (Barrett, McGuinness, and O’Connell (2024)). This section will solely focus on the derivation of the mortality assumptions and will not consider how the fertility and migration assumptions were derived.

The methodology used for setting the mortality assumption used in the official

2023-2057 National Population & Labour Force projections, was first adopted for the 2011-2041 projections, and is based on a method developed by Professor Shane Whelan (Whelan (2008)). The fundamentals of this method are based on the widely established target method which involves setting a target for life expectancy or mortality at a future point in time and outlining a path to achieve that target, guided by expert knowledge or historical trends (Booth and Tickle (2008)). The method used by the CSO requires an estimate of short-term mortality trends, an assessment of the likely long-term improvement in mortality rates from some point in the future and a method of interpolating between the current short-term and long-term trends CSO (2008)). Further details of the method are described in Appendix II of paper (Whelan (2008)).

The determination of mortality assumptions for the projections for 2023-2057 was complex due to the impact of the Covid-19 pandemic from 2020 to 2022, which substantially disrupted the mortality improvements previously observed. Furthermore, careful consideration was required in selecting the base table (the life table used as the starting point for the projections) since the period preceding the projection was affected by the Covid-19 pandemic. As a result, relying solely on recent experience for the base table was deemed inappropriate without the application of expert judgment. Further details are provided in Section 4.4.3.

4.4.2 History of Ireland's population

Ireland has witnessed significant improvements in mortality since the start of the 20th century with male life expectancy increasing from 57.4 years in 1926 to 80.2 years in 2015 (a gain of 22.8 years), while females have seen a gain of 26 years (from 57.9 to 83.9)(CSO (2024d)). The most significant increases in life expectancy for both men and women occurred in the immediate post-war period (1946–1961). These gains were driven by improvements in living conditions, advancements in maternity care, and medical innovations such as immunization (CSO (2024d)).

Figure 4.13 presents the population of Ireland from 1841 to the latest census

date 2022. As can be seen from the figure, Ireland’s population declined from the mid-19th century to the 1960’s. The decline was primarily due to the Great Famine (1845–1852), which led to mass starvation, disease, and emigration (Gráda and O’Rourke (1997)). Emigration continued throughout the late 19th and early 20th centuries due to economic hardship, leading to a steady population decrease (Fitzpatrick (1980) and Guinnane (1998)). By the mid-20th century, Ireland’s population reached its lowest point. However, from the 1960’s onward, economic policies promoting industrialisation and foreign investment helped slow emigration and eventually led to population growth (Mcgrath, Hynes, and Mchale (2022)). The ”Celtic Tiger” economic boom of the 1990’s further reversed historical trends, attracting immigration for the first time in modern history (Ruhs and Quinn (2009)).

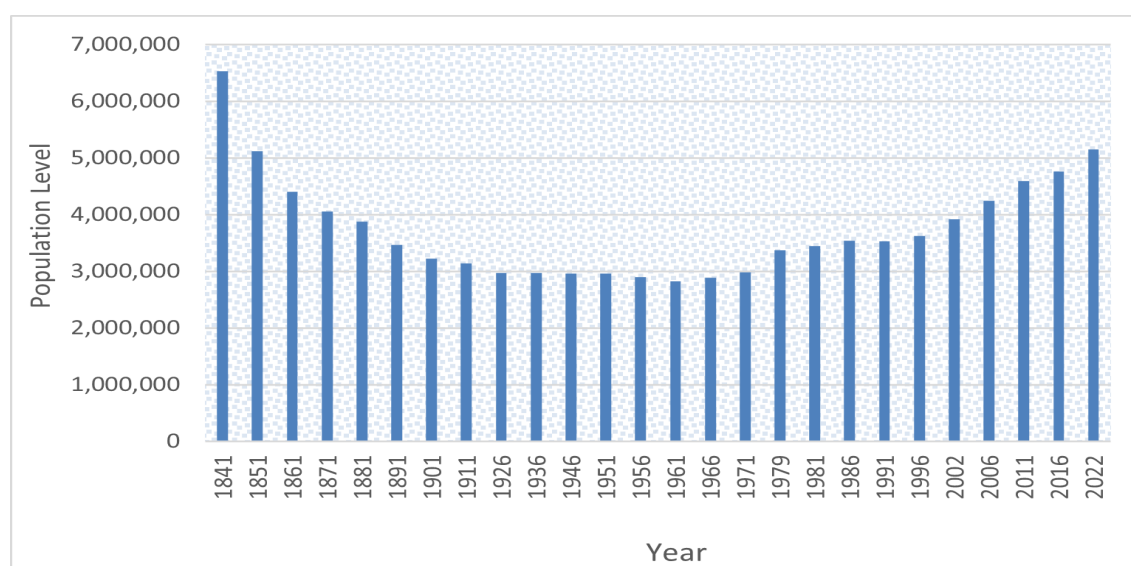


Figure 4.13: Population of Republic of Ireland 1841-2022 [Source:CSO (2025)]

4.4.3 Projections 2023-2057

The long-term rate of mortality improvements used in the previous projections (2017 - 2051) of 1.5% was deemed to be still appropriate for the 2023-2057 projections. Therefore the focus was to determine the short-term rate of mortality improvement for males and females as well as the period for the construction of the base table. In order to set the short-term mortality improvement assumption, an analysis of recent

past trends was required. Using death and population data from 2015 to 2021 (as described in Section 4.2.2), along with provisional 2022 death data from the CSO (as of April 2024) and 2022 population estimates from the CSO website (CSO 2024a), annual mortality improvements were calculated using Equation 4.1. The mortality improvement between two years, x and y for a given age group is calculated by determining the annualised average change in the ASDR for that specific age group:

$$\text{Mortality Improvement}_{x-y} = \left(\frac{\text{ASDR}_x}{\text{ASDR}_y} \right)^{\frac{1}{y-x}} - 1 \quad (4.1)$$

where:

- ASDR_x is the standardised death rate in year x ,
- ASDR_y is the standardised death rate in year y , and
- the ASDR's were standardised separately for males and females using the 2021 population for Ireland (for males and females), according to the methodology outlined in Section 4.2.3

Tables 4.8 and 4.9 show annualised mortality improvements for males and females in the three, four, and five years before the onset of the pandemic. The experience during the pandemic period 2020-2022 is also included. Since more than 80% of deaths occur after age 60, improvements are presented for both 0-90 and 60-90 age groups.

	Pre Pandemic Years (Annualised)			Pandemic Years (Annualised)
	2017-2019	2016-2019	2015-2019	2020-2022
Age 0-90	1.81%	3.00%	2.30%	0.11%
Age 60-90	2.06%	3.30%	2.40%	0.05%

Table 4.8: Male annualised mortality improvements in the 3(2017-2019), 4(2016-2019), and 5(2015-2019) years prior to the pandemic and during the 2020-2022 pandemic period, for age groups 0-90 and 60-90.

	Pre Pandemic Years (Annualised)			Pandemic Years (Annualised)
	2017-2019	2016-2019	2015-2019	2020-2022
Age 0-90	2.88%	3.45%	2.72%	-1.32%
Age 60-90	3.24%	3.56%	2.62%	-1.31%

Table 4.9: Female annualised mortality improvements in the 3(2017-2019), 4(2016-2019), and 5(2015-2019) years prior to the pandemic and during the 2020-2022 pandemic period, for age groups 0-90 and 60-90.

The results were relatively consistent across both age groups for males and females. During the pandemic period from 2020 to 2022, the annualised mortality rate was approximately 0.1% for males and around -1.3% for females, regardless of age group. In contrast, over the three, four, and five years preceding the pandemic, annualised mortality improvements generally ranged from 2.0% to 3.3% for males and were higher for females, ranging from 2.6% to 3.6%.

The Covid-19 pandemic disrupted the observed trend of mortality improvement from 2000 to 2019. To adjust for this temporary increase in mortality, one option is to exclude deaths attributed to Covid-19 from the rates in these years. However, this approach presents several challenges. First, cause-of-death classifications are often unreliable—individuals who died from Covid-19 but had underlying conditions may have been misclassified, or they might have died from other causes regardless. Secondly, lockdown measures reduced the spread of other respiratory illnesses, such as the flu, which affect seasonal mortality rates. Thirdly, lifestyle and behavioral changes during lockdown led to fewer deaths from other causes, such as traffic accidents. As previously noted in Table 4.2, excess deaths in Ireland in 2020/2021 were relatively low at c.1,100. Given these factors, the pandemic years were considered a short-term anomaly and excluded from setting the short-term mortality improvement assumption. The short-term rate of mortality improvement was based on pre-pandemic experience, with a 2.5% annual improvement deemed reasonable for both males and females. This represents a slight change from previous projections, which assumed a short-term rate of 2.5% for males and 2.0% for females.

As of April 2024, when the 2023-2057 projections were being calculated, only

provisional death data was available for 2022, and the CSO indicated that these figures were significantly under-reported. Furthermore, the Covid-19 pandemic was still present in 2022 albeit its impact had been largely mitigated through vaccinations, natural immunity, and other factors. Therefore, it was determined that the 2022 mortality experience should not be included in the base table for the projection. Furthermore, to avoid any risk of projection of the pandemic experience as a longer-term trend, mortality data from any pandemic year should be excluded from the calculation of the base table. Instead, the base table for 2022 was derived from the mortality experience of the three years preceding the pandemic (2017–2019). A three-year period was selected over a single year to ensure consistency with previous projections and to provide a more stable and representative average. By using the 2017–2019 data to calculate the base table in 2022, it implicitly assumes that mortality in Ireland returned to pre-pandemic levels by that year. Other research supports this assumption. For instance, a report by the ONS in 2020 projected that the increase in mortality rates observed in 2020 for individuals aged 30+ would largely reverse by 2022, with subsequent improvements aligning with pre-pandemic projections (ONS (2020)). Furthermore, according to the United Nations World Population Prospects, global life expectancy, which had dropped significantly in 2020 and 2021, returned to 2019 levels by 2022 (Ritchie and Rod  s-Guirao (2024)). However, some studies suggest a longer recovery period. Huang et al (2023) found that life expectancy in 22 of the 27 countries studied had yet to return to pre-pandemic levels in May 2023. Similarly, the Centraal Bureau voor de Statistiek in the Netherlands reported that, as of November 2023, mortality had still not fully recovered to pre-pandemic levels (CBS (2023)). Finally, the Continuous Mortality Investigation (CMI), a research unit of the IFoA, publish annual population projections using an in house model namely the CMI model (CMI (2022)). The CMI model is the most popular model used by insurers and pension schemes in the UK to express views of future mortality (Hymans Robertson (2023)). It is calibrated to population mortality data and uses recent trends used to inform the short-term rate of improvement.

Since the onset of the pandemic, the CMI model used to prepare the projections has been modified to enable users to apply different weights to data from individual years. For the 2023 CMI model (the most recent version as of 01st April 2025), the weights were allocated as follows: 0% for data from 2020 and 2021, 15% for data from 2022 and 2023, and 100% for data from all other years (Hymans Robertson (2023) and CMI (2023)). This adjustment reflects that, as of the end of 2023, mortality rates had not yet returned to the pre-pandemic levels seen in 2019. According to the CMI, mortality in England & Wales for 2023 was 3% higher than the 2019 benchmark, but still lower than in 2020, 2021, and 2022 (CMI (2024a)).

Figure 4.14 presents the mortality rates for the 2022 base table, which is based on the 2017–2019 experience, alongside the base tables used in two previous projections for both males and females. All tables were graduated using the Kings method (King (1909)). As shown, the mortality rates across all base tables are quite similar.

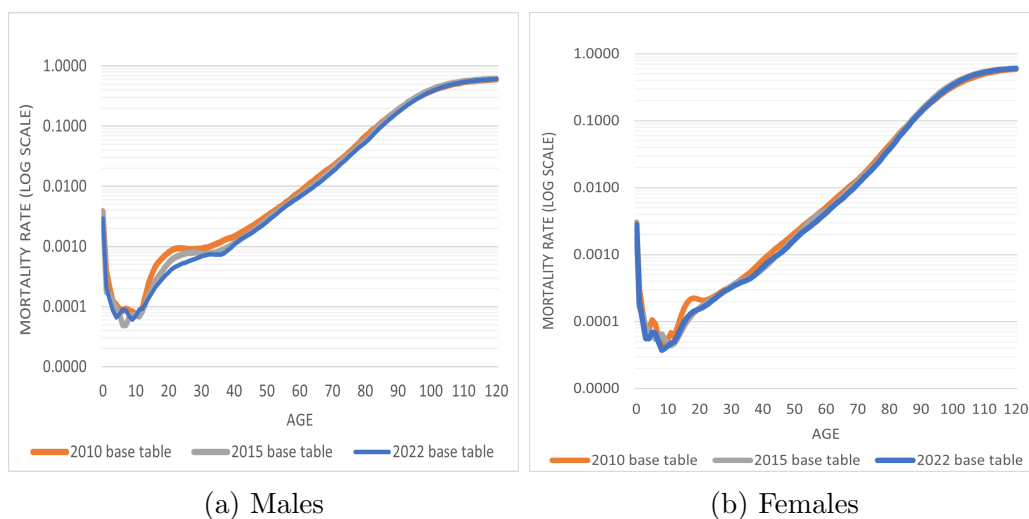


Figure 4.14: Comparison of base table from 2010, 2015 and 2022 population projections.

To summarise, the mortality assumptions underlying the official 2023-2057 National Population & Labour Force Projections are as follows:

- Mortality rates for both males and females are assumed to improve at an annual rate of 2.5% in the short term, defined as the first 25 years of the projection period.

- The long-term rate of mortality improvement remains unchanged from the previous projection at 1.5% per annum.
- Over the 25-year period, the short-term rate is assumed to decline linearly to the long-term rate.
- These improvement rates apply to all ages up to 90.
- For individuals aged 100 and over, no mortality improvement (0%) is assumed.
- For ages 91 to 99, the improvement rate is determined through linear interpolation between the 2.5% rate at age 90 and the 0% rate at age 100

These assumptions will result in gains in life expectancy from:

- 80.2 years in 2022 to 86.2 years in 2057 for males.
- 83.9 years in 2022 to 89.1 years in 2057 for females.

Figure 4.15 presents the population projections for the period 2022–2057 which incorporates the mortality assumptions set out above. While a single scenario was used for both mortality and fertility, three different inward migration scenarios (high, medium, and low) were included due to the heightened uncertainty surrounding immigration, particularly in light of the ongoing war in Ukraine. The official projections were published on the 16th July 2024 on the CSO website (2024).

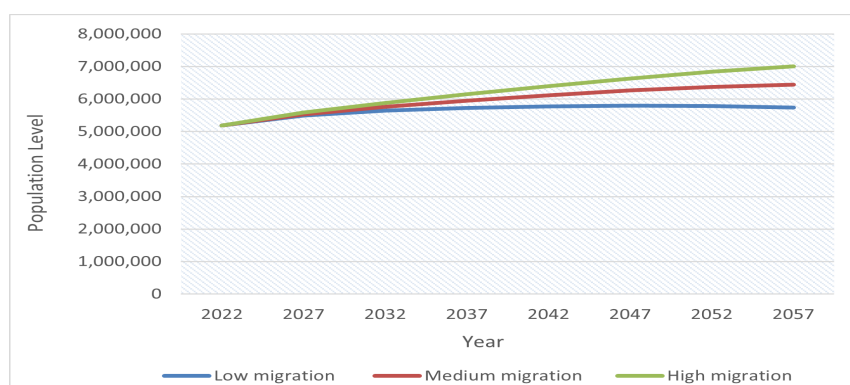


Figure 4.15: Projected Population Level 2022–2057 [Source: CSO (2024b).]

Chapter 5

UK Occupational Pension Scheme Ill-Health Retirement Mortality Experience

5.1 Introduction

Occupational pension schemes provide benefits for employees in retirement and are an important part of an employee's overall remuneration. Such schemes are funded by contributions from employers and employees prior to retirement. Common benefits include member pensions, spouse pensions, lump sum benefits on retirement and ill-health benefits (Citizens Advice (2024)). Traditionally, there have been two main types of pension scheme - Defined Benefit (DB) schemes where benefits are fixed in advance and the contributions vary as required to fund the benefits and Defined Contribution (DC) schemes where contributions are fixed and the ultimate benefits depend on the accumulated value of the contributions at retirement. Other newer types of pension schemes include Personal Retirement Savings Accounts (Ireland), Self-Invested Pension Plans (UK), Auto-Enrolment Schemes, Flexible & Hybrid Schemes, and Collective Defined Contribution Schemes (Citizens Information (2024b), UK Government (2024), *Auto Enrolment* (2024), The Pensions Trust

(2024), and Citizens Information (2024a)). Many of these operate similarly to DC schemes or combine elements of DB and DC schemes. The high costs and risk associated with the provision of guaranteed benefits under DB schemes has led to the closure of large numbers of DB schemes in recent years (Smith and MacLaren (2011), Irish Association of Pension Funds (2018), House of Commons Work and Pensions Committee (2024), and Sutcliffe (2016)) with new employees typically being offered DC type arrangements. Nonetheless, DB schemes continue to be a major component of the pensions industry. For example in Ireland, in 2021, current and former Public Sector employees had DB pension benefits valued at €176 billion which included the pension accrued for c.336,000 active members and c.192,000 retirees (O'Brien 2024; The Irish Times 2024). Additionally, statistics from the Pension Regulator for private DB schemes in Ireland show that in 2023, there were 64,270 active members, 121,380 deferred pensioners, and 109,033 pensioners in DB schemes, with total liabilities amounting to €49.4 billion (Pensions Authority 2024). Across Europe, the corresponding DB pension liability at the end of 2023 was €1,846 billion (European Central Bank (2023)).

Funding for DB pension schemes requires accurate models of the current and future mortality of their retirees. Retirements from the workforce can be split between those who are forced to retire early specifically for health reasons referred to as ill-health retirements and all other retirements referred to as normal health retirements. Normal health retirements, which include those who retire at normal retirement age and those who choose to retire at earlier or later ages fortunately form the majority of retirements from occupational pension schemes. However, funding for ill-health pensioners can be expected to become more important for pension schemes in the future. First, the aging population has motivated national governments and bodies such as the European Union to develop policies for encouraging the labour force participation of older workers and eliminating mandatory retirement ages (Cooke (2006)). Furthermore, many countries are facing pressure to raise the age at which state retirement benefits are payable, as the traditional 'pay-as-you-go' pension sys-

tem is under strain due to declining birth rates (Honekamp (2007)) and increasing life expectancy (Ayuso et al. (2021)). Rates of retirement in ill-health increase with age and as pension schemes increase their normal retirement age in line with increasing life expectancy and government policies, the number of ill-health retirements can also be expected to increase. Secondly, females tend to experience higher rates of chronic illness than males and are therefore more likely to be in receipt of a disability pension (Claussen and Dalgard (2009) and Haukenes et al. (2012)). Therefore, as the proportion of women in the workforce (and subsequently in occupational pension schemes) increases the number of ill-health retirements can also be expected to rise.

Pension scheme members seeking to retire on ill-health grounds must prove they are in sufficiently poor health (mental and/or physical) that they are prevented from performing their normal employment and that the incapacity is likely to be permanent. Typically, for defined benefit occupational pension schemes, the terms available on ill-health retirement are more generous than those available under normal-health retirement. This reflects the fact that the individual taking ill-health retirement is being forced to retire early for health reasons rather than choosing to do so for lifestyle reasons. For example, there may be no minimum age for ill-health retirement and the ill-health retirement pension may be based on prospective pensionable service to normal retirement age rather than actual service. Nonetheless ill-health retirement pensioners can expect to receive a lower pension than if they had of been able to retire normally.

Mortality is strongly related to socioeconomic status (SES), which is often measured by income, education or occupation, with lower SES associated with higher mortality (Woolf et al. (2007)). In retirement an individual's SES is likely to be highly correlated with their pension income. According to a study funded by the European Commission in 2017 (Stringhini et al. (2017)), low socioeconomic status is linked to significant reductions in life expectancy and should be considered a major risk factor for ill health and early death in national and global health policies. Looking at income, the study found that when individuals were compared with their

wealthier counterparts, people with low socioeconomic status were 46% more likely to die early (under 85 years). Socioeconomic differences in mortality also persist beyond retirement age and in magnitude increase with age (Marmot and Shipley (1996) and Feinglass et al. (2007)). The mortality of pensioners is known to vary with pension amount with those on lower pensions experiencing higher mortality relative to those with higher (Madrigan et al. (2011), Taubman (1981), and Majer et al. (2011)). However, the impact of pension on the mortality of ill-health retirement pensioners has not been investigated. Furthermore, SES tends to influence male and female mortality differently. A study carried out by Phillips & Hamberg (2015) showed that females of all SES levels tended to outlive males at the same level and the gap in health between lowest and highest socio-economic grade was narrower for females compared to males.

In 2002 the Continuous Mortality Investigation (CMI) of the Institute and Faculty of Actuaries, UK, commenced an investigation into the mortality experience post retirement of UK pensioners in Self-Administered Pension Schemes (SAPS) (CMI (2001)). As a result of this investigation the CMI produced life Tables in 2007 based on the 2001-2006 experience (the “S1” Tables) and in 2014 based on the 2004-2011 (the “S2” Tables). The life Tables were based on age, gender and pension band for normal-health retirement pensioners and on age and gender only for ill-health retirement pensioners (CMI (2008a), CMI (2008b), CMI (2013b), and CMI (2014)). The CMI carried out additional analysis on the impact of Industry sector on the mortality of Normal Health pensioners but did not graduate life Tables by industry. In general, the CMI found that the mortality of its Public Sector dataset is lower than that its Private Sector dataset (CMI (2023)). Due to the lack of comparable life Tables for the Irish pensions industry, the CMI SAPS Tables are widely used by the Irish actuarial profession for valuations of Irish DB pension schemes.

Poor health has a cumulative effect on mortality and ill-health pensioners who retire at younger ages will spend longer in poor health and consequently experience higher mortality relative to those who retire at later ages. Hall & Daly (2016),

using the “S2” data, analysed the mortality experience of the ill-health pensioners by age at retirement and duration since retirement. They modelled the reverse select mortality of the ill-health pensioners using 1-dimensional GAMS – with males having a reverse select period of 4 years and females having a reverse select period of 5 years. Hall & Daly (2016) also highlight the importance of accounting for the effect of retirement age when modeling the mortality of pensioners retiring due to ill health and used 2-Dimensional GAMS to model the ultimate mortality experience of the ill-health pensioners by age group at retirement. Research for normal health retirees also indicates that early retirees experience higher excess mortality compared to those who retire later (Wu et al. (2016) and Hosmer (1956)). Considering the significant impact of retirement age on future life expectancy, all of the modelling in this chapter is carried out separately by retirement age along with gender.

This chapter extends previous published work which modelled the reverse select and ultimate mortality experience of UK ill-health retirement occupational pension scheme members (Hall and Daly (2016)). In particular it extends the analysis of the ill-health retirement pensioners, using the “S2” data, to model the effect of pension amount and industry sector on the ultimate mortality of the pensioners. Due to small data volumes it is not possible to model the reverse select experience by these factors. The chapter is structured as follows:

- **Section 5.2** – Presents the data utilised in the analysis.
- **Section 5.3** – Outlines the methodology applied to conduct the analysis.
- **Section 5.4** – Examines the mortality of ill-health pensioners (modelled separately by age group at retirement & gender) focusing on:
 - Age
 - Age & Pension Band level (as a proxy for SES)
 - Age & Industry Sector
- **Section 5.5** – Expands the analysis carried out in section 5.4 by analysing the joint impact of Age, Pension Band & Industry Sector on mortality.

-
- **Section 5.6** – Provides a discussion and conclusion of the results.

5.2 Data

In 2013 the CMI released the “S2” series of mortality Tables based on the mortality experience of UK Self Administered Pension Schemes (SAPS) over the period 2004 to 2011. The “S2” series of Tables include graduated life Tables for normal health, ill-health and dependant pensioners. Further details on the SAPS data and the graduation of the “S2” series Tables can be found in CMI working papers 65, 66 and 71 (CMI (2013a), CMI (2013b), and CMI (2014)). The CMI has kindly made the data underling the “S2” ill-health life Tables available for this analysis. This comprises approximately 345,000 male lives and 240,000 female lives. Ill-health retirements are, fortunately, less common than normal health retirements in the UK. For comparison for the SAPS data collected by the CMI for the period 2004-2011 the exposure for the ill-health pensioners is approximately 1/6th and 1/5th that of the exposure for normal health pensioners for males and females respectively. The data made available for this analysis included the gender, date of birth, end pension amount, date of retirement, industry pensioner previously employed in, date of death where applicable and the exposure period for each pensioner. The date of retirement was missing for less than 2% of the records.

Ill-health retirement mortality exhibits higher mortality immediately following retirement (referred to as reverse select mortality) before declining in subsequent years. Previous research (Hall and Daly (2016)) indicated a reverse select period for ill-health retirement pensioners of 4 year for males and 5 years for females. The deaths and exposures were calculated excluding the first 4 years of data following retirement for males and the first 5 years of data following retirement for females. To avoid distortions due to low data volumes, data during this reverse select period is excluded from the analysis. The deaths and exposures were calculated up to age 90 in each case.

For the analysis the ill-health retirement pensioners were divided into three groups depending upon their age at retirement(ages 45-54, 55-59 and 60-65). Re-

tirements below age 45 and after age 65 were excluded due to the low data volumes available for analysis. The ill-health pensioner data included approximately 25,000 and 23,000 new male and female retirements during the period 2004 to 2011 and Figure 5.1 shows the proportion of new ill-health retirements by age group. The average age of retirement was 55.4 for males and 54.1 for females. There are proportionally slightly more ill-health retirements at younger ages (<50) for females relative to males. In general, however, the proportions retiring within each age group are relatively similar for males and females. As expected the number of ill-health retirements increases with age with almost 80% occurring after age 50.

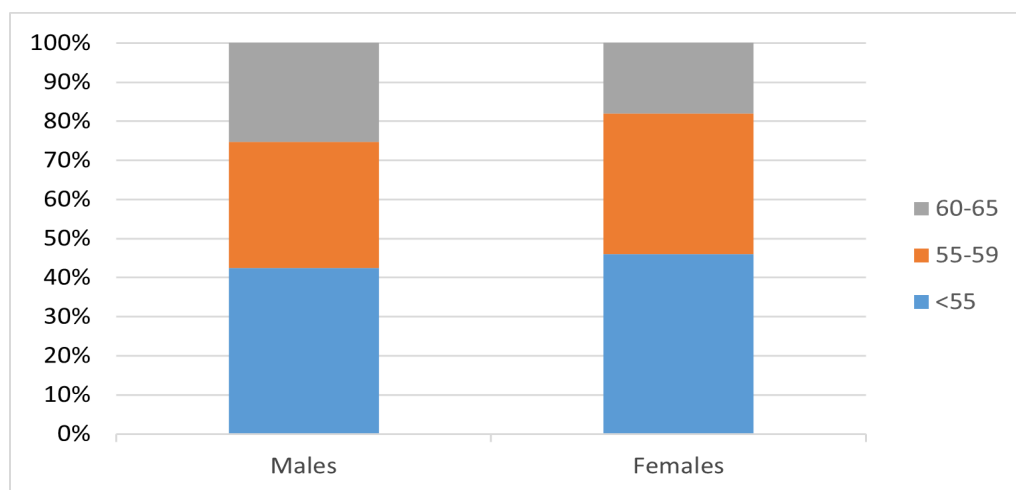


Figure 5.1: Proportion of ill-health retirements by *Age Group at Retirement* for new retirements over the period 2004-2011 for males and females.

5.2.1 Data by Age Group at Retirement

The ill-health retirement pensioners were classified into three groups based on their retirement age: 45-54 (referred to as <55 throughout the rest of the chapter), 55-59, and 60-65. Deaths and exposures for each of the three groups were calculated for males and females respectively. Exposures were calculated using the central exposed to risk method. Table 5.1 presents the deaths and exposures for males and females over the period 2004-2011 by *Age Group at Retirement*. As can be seen, the number of deaths for males were more than double that of females.

Age Group at Retirement	Males (Exposures/Deaths)	Females (Exposures/Deaths)
< 55	299,883 / 8,204	199,632 / 3,426
55-59	196,441 / 9,262	166,172 / 4,941
60-65	122,605 / 7,828	64,910 / 2,945
Total	618,929 / 25,294	430,714 / 11,312

Table 5.1: Deaths & Exposures by *Age Group at Retirement*.

Figure 5.2 presents the proportion of deaths by *Age Group at Retirement* for both males and females. The proportion of deaths for those who retired under age 55 is very similar for both males and females. However females had a larger proportion of deaths in the 55-59 group whereas males had a larger proportion of deaths in the 60-65 group.

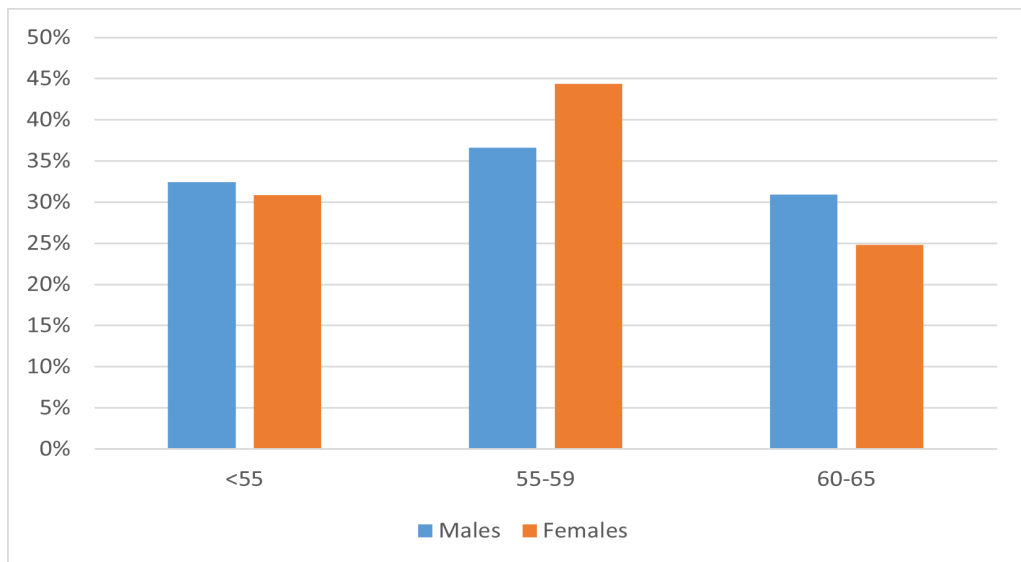


Figure 5.2: Proportion of deaths by *Age Group at Retirement* over the period 2004-2011 for males and females.

5.2.2 Data by Age Group at Retirement & Pension Band

To analyse the impact of pension level on the mortality of ill-health retirement pensioners, the pensioners in each *Age Group at Retirement* were divided into three *Pension Bands*, with separate bands for males and females. To ensure a balanced distribution of data within each *Pension Band*, a weighted average *Pension Band*

was determined based on the 'end pension level' at the 33rd and 66th percentile for each of the three retirement groups. The weighted average *Pension Band* at the 100th percentile was assumed to equal the maximum pension amount in the dataset to prevent any data loss. The *Pension Bands* were calculated as follows:

For $i = 1, 2, 3$:

- x_i = Number of retirees in the Age Group at Retirement i .
- $P_{i,33}$ = 33rd percentile of the End Pension amount in Age Group at Retirement i .
- $P_{i,66}$ = 66th percentile of the End Pension amount in Age Group at Retirement i .

where:

- Pension Band 1 = $\frac{\sum_{i=1}^3 x_i \cdot P_{i,33}}{\sum_{i=1}^3 x_i}$
- Pension Band 2 = $\frac{\sum_{i=1}^3 x_i \cdot P_{i,66}}{\sum_{i=1}^3 x_i}$
- Pension Band 3 = maximum level of End Pension amount in the dataset.

Table 5.2 presents the resulting *Pension Bands* for males and females and Table 5.3 shows the corresponding number of deaths and exposures for males and females from 2004 to 2011, broken down by *Age Group at Retirement* and *Pension Band*.

Pension Band (Percentile)	Males	Females
1 (33rd)	£3,634	£2,270
2 (66th)	£6,972	£4,204
3 (100th)	£165,386	£85,821

Table 5.2: *Pension Band* thresholds at the 33rd, 66th, and 100th percentiles for males and females.

Age Group at Retirement	Pension Band	Males (Exposures/Deaths)	Females (Exposures/Deaths)
<55	1	72,704 / 3,050	53,914 / 1,154
	2	98,995 / 2,769	65,467 / 1,229
	3	128,184 / 2,385	80,251 / 1,043
55-59	1	62,025 / 3,828	46,524 / 1,686
	2	67,543 / 3,069	61,945 / 1,980
	3	66,873 / 2,365	57,703 / 1,275
60-65	1	65,888 / 4,765	27,483 / 1,388
	2	37,305 / 2,104	22,177 / 985
	3	19,412 / 959	15,250 / 572
Total		618,929 / 25,294	430,714 / 11,312

Table 5.3: Deaths & Exposures by *Age Group at Retirement* and *Pension Band* over the period 2004-2011 for males and females.

5.2.3 Data by Age Group at Retirement & Industry Sector

To analyse the impact of industry on the mortality of ill-health retirement pensioners, the pensioners were split by *Industry Sector*. The volume of data varies by sector and Figures 5.3(a) and 5.4(a) show the proportion of males and females in each industry. Some industries have very few individuals, especially among females, which led to the decision to group the data. For both males and females, the Public Sector & Local Authority groups dominated the data. These groups were combined into a single category, as both represent state-employed individuals, making up 61% and 85% of the overall male and female data. Due to the smaller data sizes of the remaining industries, they were grouped into a Private Sector category, ensuring identical groupings for both males and females. This also simplifies the comparative analysis of the impact of industry between males and females. Figures 5.3(b) and 5.4(b) present the proportion of males and females within this paired grouping: Public Sector & Local Authority and Private Sector.

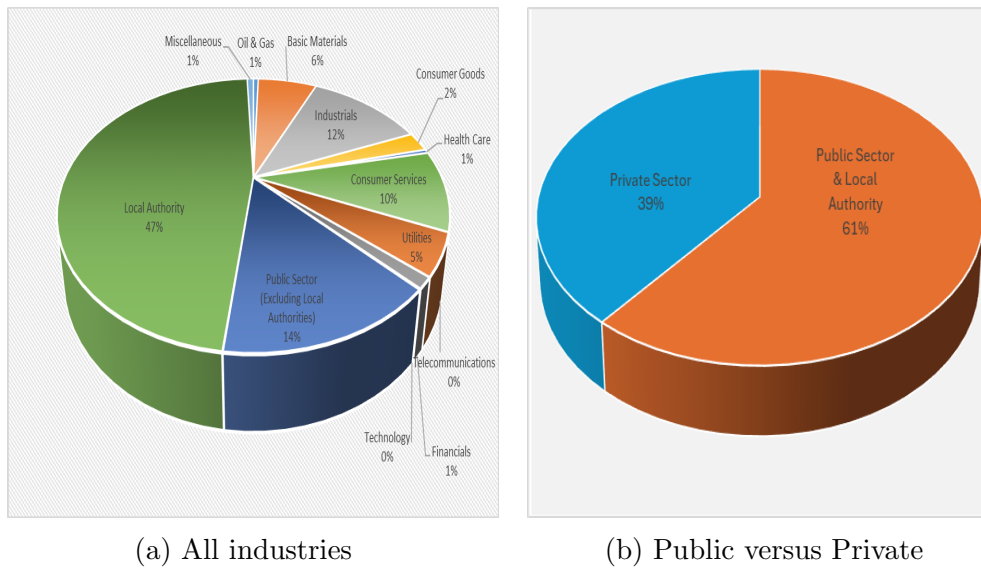


Figure 5.3: Proportion of male lives by *Industry* sector

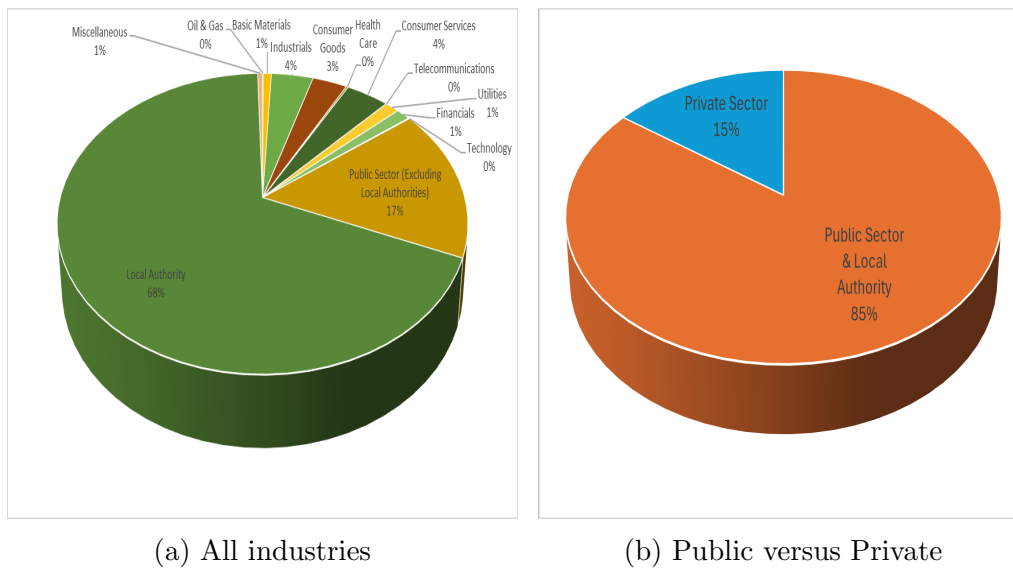


Figure 5.4: Proportion of female lives by *Industry Sector*

Table 5.4 shows deaths and exposures for males and females from 2004 to 2011, broken down by *Age Group at Retirement* and *Industry Sector*. For all three *Age Group's at Retirement*, the number of deaths for females in the Private Sector is relatively small, and this should be taken into account for any future mortality modelling for females in the Private Sector.

Age Group at Retirement	Industry Sector	Males (Exposures/Deaths)	Females (Exposures/Deaths)
<55	Public & Local Authority	189,114 / 4,806	167,508 / 2,755
	Private Sector	110,769 / 3,398	32,124 / 671
55-59	Public & Local Authority	124,290 / 5,668	147,126 / 4,338
	Private Sector	72,151 / 3,594	19,046 / 603
60-65	Public & Local Authority	98,734 / 6,250	62,367 / 2,845
	Private Sector	23,871 / 1,578	2,543 / 100
Total		618,929 / 25,294	430,714 / 11,312

Table 5.4: Deaths & Exposures by *Age Group at Retirement* and *Industry Sector* over the period 2004-2011 for males and females

5.2.4 Data by Age Group at Retirement, Pension Band & Industry Sector

To analyse the combined impact of *Pension Band* and *Industry Sector* on the mortality of ill-health retirement pensioners, the data was further segmented by both *Pension Band* and *Industry Sector*. Table 5.5 presents the deaths and exposures for males and females from 2004 to 2011, categorised by *Age Group at Retirement*, *Pension Band* and *Industry Sector*. The number of deaths among females in the Private Sector groups across all three pension bands (but particularly for those who retired between the ages of 60-65) is too small to carry out any statistical modeling. Therefore, modelling the combined effect of *Pension Band* and *Industry Sector* will only be performed for males.

Age Group at Retirement	Pension Band	Industry Sector	Males		Females	
			Exposures	Deaths	Exposures	Deaths
<55	1	Public & Local Authority	44,999	1,900	43,635	887
	2	Public & Local Authority	68,880	1,761	55,575	1,008
	3	Public & Local Authority	75,235	1,145	68,298	860
	1	Private Sector	27,705	1,150	10,279	267
	2	Private Sector	30,115	1,008	9,892	221
	3	Private Sector	52,949	1,240	11,953	183
55-59	1	Public & Local Authority	39,970	2,476	37,210	1,382
	2	Public & Local Authority	44,151	1,834	56,332	1,803
	3	Public & Local Authority	40,169	1,358	53,584	1,153
	1	Private Sector	22,055	1,352	9,314	304
	2	Private Sector	23,392	1,235	5,613	177
	3	Private Sector	26,704	1,007	4,119	122
60-65	1	Public & Local Authority	56,046	4,007	25,968	1,330
	2	Public & Local Authority	29,813	1,601	21,646	964
	3	Public & Local Authority	12,875	642	14,753	551
	1	Private Sector	9,842	758	1,515	58
	2	Private Sector	7,492	503	531	21
	3	Private Sector	6,537	317	497	21
Total			618,929	25,294	430,714	11,312

Table 5.5: Deaths & Exposures by *Age Group at Retirement*, *Pension Band*, and *Industry Sector* over the period 2004-2011 for males and females.

5.3 Methodology

The mortality experience is analysed using age standardised death rates (ASDR) and generalized additive models (GAMs). The ASDRs provide an initial analysis of the data while the GAMs produced smoothed age specific estimates of the mortality rates. Separate analyses are carried out for males and females respectively where applicable.

The ASDR were calculated using the method described in Section 2.2.3 using the European Standard Population (Eurostat (2013)). For comparison across the different age at retirement groups the ASDR were calculated for age range 65-85 in each case. The formula used to calculate the ASDRs is repeated below:

$$\text{ASDR} = \frac{\sum_x (\hat{m}_x \cdot {}^sP_x)}{\sum_x {}^sP_x}, \quad (5.1)$$

where:

$\hat{m}_x$ = crude death rate at age x last birthday in the population,

${}^sP_x$ = the standard population exposed to the risk of death at age x
last birthday.

The crude death rate is given by:

$$\hat{m}_x = \frac{d_x}{E_x^c}, \quad (5.2)$$

where:

$d_{x,t}$ is the number of deaths observed at age x last birthday during year t ,

E_x^c denotes the central exposed to the risk for individuals age x .

The GAMs assume that deaths follow a Poisson distribution and were fitted using the approach outlined in Section 3.3.3. Smoothing was applied using thin plate regression splines (Wood (2003) and Wood (2006)), ensuring that the GAMs produce smooth estimates of mortality rates by age.

5.4 One and two factor analysis

This section examines the impact of the following factors on ill-health pensioner mortality, analysed separately by *Age Group at Retirement* & gender:

- Age
- Age & Pension Band
- Age & Industry Sector

5.4.1 Preliminary Analysis

As a preliminary analysis, Figure 5.5 presents the overall male and female crude mortality rates by individual factor. The overall crude rate was calculated separately for males and females for each factor as follows:

$$\hat{m}_x = \frac{\sum_{x=65}^{90} d_x}{\sum_{x=65}^{90} E_x^c} \quad (5.3)$$

where d_x represents the number of deaths occurring at age x and E_x^c denotes the central exposed to the risk for individuals age x .

Note: The summation for each factor is performed over the age range 65-90 to ensure a fair comparison across retirement groups. The only exception is for the *Age* factor, where the summation is applied over the corresponding age range.

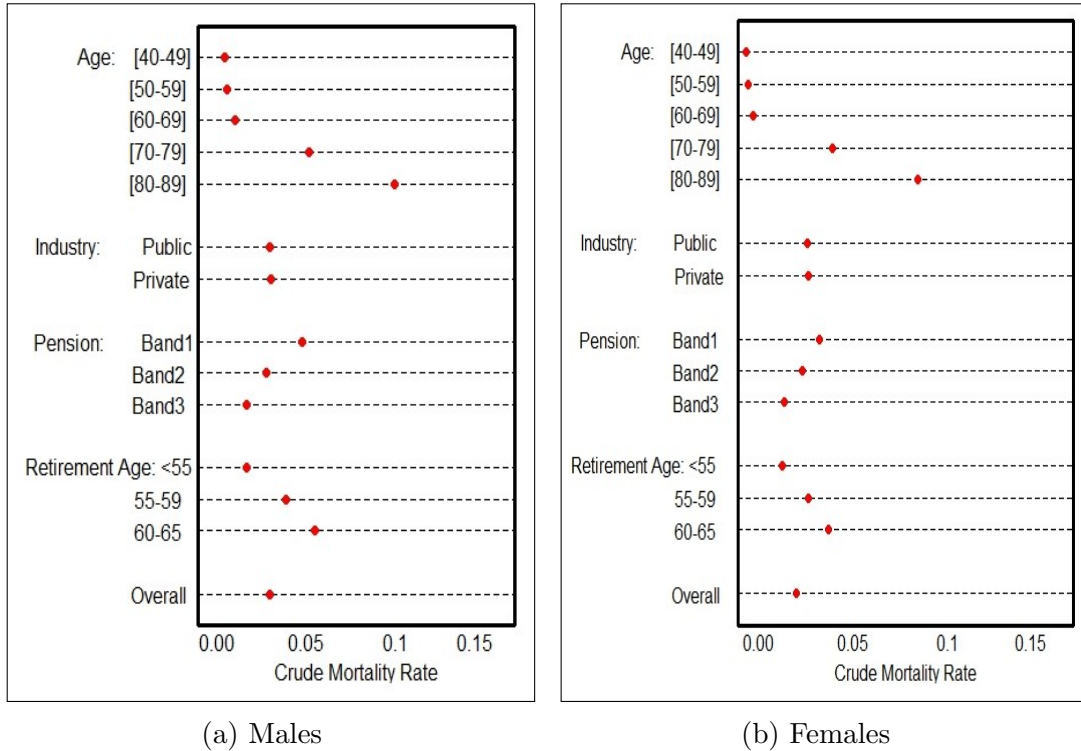


Figure 5.5: Crude mortality rates for males and females by individual factor.

For both males and females, the observed effects for age and pension band align with intuitive expectations. For example, younger individuals generally exhibit lower

mortality rates compared to older ones, and those receiving lower pensions (Pension Band 1) have higher mortality rates than those receiving higher pensions (Pension Band 3).

An unexpected finding in the analysis pertains to the influence of *Industry Sector* on mortality rates. The data was categorised into two groups (Public Sector & Local Authority and Private Sector) and this analysis reveals minimal differences in crude mortality rates between the groups. This contrasts with previous research suggesting that Public Sector workers generally experience lower mortality rates compared to their Private Sector counterparts (Munnell, Aubry, Sanzenbacher, et al. (2015), Niraula (2019), and Bauleo et al. (2023)).

Furthermore, the crude analysis indicates that individuals who retire at younger ages tend to exhibit lower mortality rates compared to those who retire later, a finding that contradicts existing research. In contrast, prior studies suggest that health deterioration accumulates over time, leading to ill-health pensioners who retire earlier experiencing prolonged periods of poor health and, consequently, higher mortality rates than those who retire later (Wu et al. (2016) and Heide et al. (2013)). However, since the analysis is based on average crude mortality rates over the age range of 65 to 90, there is a possibility that some individuals who retired at younger ages (e.g., before age 55) may have died before reaching age 65, which could introduce bias into the results.

Overall, this analysis highlights the importance of recognising that crude mortality rate comparisons can be misleading, as the populations being compared may differ significantly in other underlying characteristics that influence overall mortality rates.

5.4.2 Analysis of Mortality by Age

Table 5.6 presents the ASDR's by *Age Group at Retirement* over the age range 65-85. The results are presented separately for each *Age Group at Retirement*, as well as for males and females:

Age Group at Retirement	Males	Females
<55	5.8%	3.5%
55–59	5.1%	3.2%
60–65	5.0%	3.0%

Table 5.6: ASDR by *Age Group at Retirement* for males and females aged 65–85.

As expected, the ASDR for both males and females decreases as the *Age Group at Retirement* increases, with the most notable drop observed when comparing the under 55 group to the 55–59 group. Specifically, the ASDR declines by approximately 12% for males and 9% for females between these groups. However, for males, the decrease is marginal—about 2%—when comparing the 55–59 group to the 60–65 group. In contrast, females experience a more pronounced decline of around 6% across the same age range.

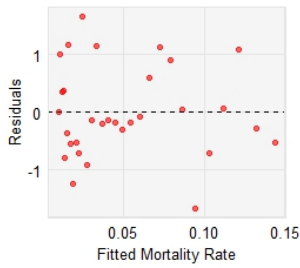
Poisson GAMs were used to model the mortality of the ill-health retirement pensioners by *Age* only across the three *Age at Retirement groups* as follows as follows:

$$\log(\mu'_x) = \beta_0 + f_1(\text{Age}_x) + \log(E_x^c) \quad (5.4)$$

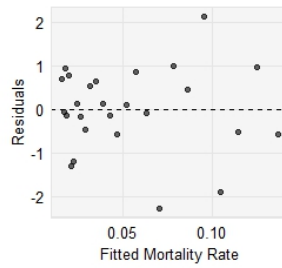
Table 5.7 presents the results of fitting the model separately to the male and female data in Table 5.1, while Figures 5.6 and 5.7 present the corresponding residual plots. In each case the models provide a good fit to the data with relatively simple smooth terms (as indicated by the low effective degrees of freedom (EDF)). The p-values for all terms, for both males and females, were highly significant (all zero to six decimal places).

Age Group at Retirement	Age Range	Males			Females		
		B_0	$f_1(\text{EDF})$	Adj R^2	B_0	$f_1(\text{EDF})$	Adj R^2
<55	55–85	-3.29651	3.367	98.5%	-3.80232	4.525	92.0%
55–59	60–85	-3.15113	4.054	98.4%	-3.72456	1.345	98.4%
60–65	65–85	-2.99117	1.329	99.2%	-3.51209	1.259	98.9%

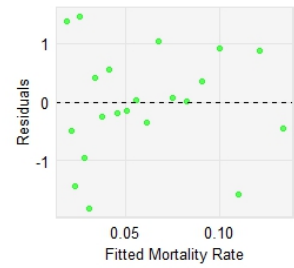
Table 5.7: B_0 (intercept) estimates, EDF for smooth function f_1 , and adjusted R^2 values, by *Age Group at Retirement* and gender, fitted over the specified age ranges.



(a) Retirement age < 55

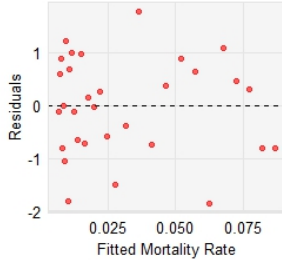


(b) Retirement age 55 - 59

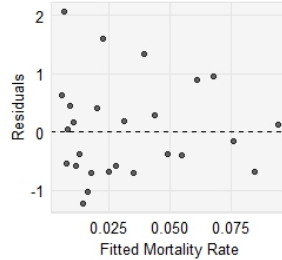


(c) Retirement age 60 - 65

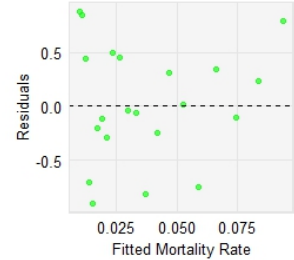
Figure 5.6: Male residual plot from GAMs containing smooth function of *Age*.



(a) Retirement age < 55



(b) Retirement age 55 - 59



(c) Retirement age 60 - 65

Figure 5.7: Female residual plot from GAMs containing smooth function of *Age*.

Figure 5.8 plots the mortality rates from the fitted models for each *Age Group at Retirement* for males and females. Consistent with the initial analysis using ASDR the mortality rates tend to decrease with increasing retirement age with those retiring under age 55 showing a clear gap in mortality relative to those retiring at older ages (particularly for males). At higher ages, males show a convergence in mortality for those retiring between ages 55-59 and 60-64, while those who retired under 55 show the highest mortality. Females show a crossover in mortality rates at older ages, but this may be due to the smaller number of deaths among females

who retired prior to age 55 (see Table 5.1).

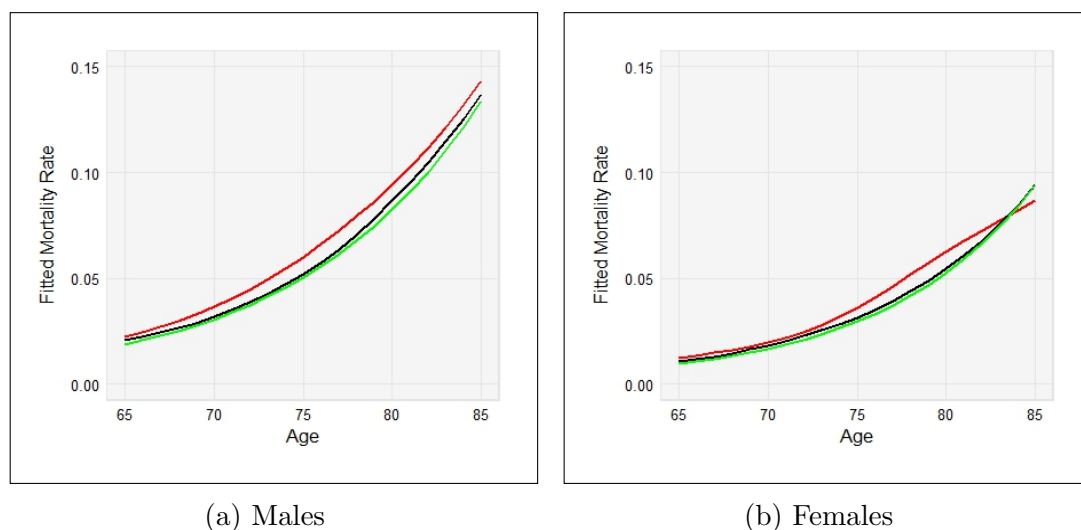


Figure 5.8: Mortality rates for males and females by *Age Group at Retirement*, as modelled by GAMs using smooth function of *Age*: <55 (—), 55–59 (—), and 60–65 (—).

5.4.3 Analysis of mortality by Age and Pension Band

Table 5.8 presents the ASDRs by *Pension Band* for each *Age Group at Retirement* for males and females respectively over the age range 65–85.

Age Group at Retirement	Males			Females		
	Pension Band 1	Pension Band 2	Pension Band 3	Pension Band 1	Pension Band 2	Pension Band 3
<55	6.7%	5.6%	4.8%	3.9%	3.4%	3.1%
55–59	6.3%	5.1%	4.0%	3.8%	3.2%	2.6%
60–65	5.4%	4.7%	3.9%	3.3%	3.0%	2.6%

Table 5.8: ASDR by *Age Group at Retirement* and *Pension Band* for males and females aged 65–85.

As expected, for males the ASDRs decrease as both the *Pension Band* and the *Age Group at Retirement* increases. Similarly, for females the ASDR generally decreases with higher levels of pension and later retirement ages. However, an exception is noted for females retiring between ages 60–65 in *Pension Band 3*, where the ASDR remains unchanged compared to those retiring between ages 55–59 within the same *Pension Band*. Males show a greater relative difference between

the *Pension Bands* compared to females, indicating that *Pension Band* has a more significant impact on the mortality of male ill-health retirement than females. This is consistent with the analysis of the impact of *Pension Band* on the mortality of normal health retirement pensioners (CMI (2024b), Mackenbach et al. (2008), and Marmot and Shipley (1996)).

Poisson GAMs were used to model the mortality of the ill-health retirement pensioners by *Age* and *Pension Band* across the three *Age at Retirement* groups as follows:

$$\log(\mu'_x) = \beta_0 + \text{PensionBand} + f_1(\text{Age}_x) + f_2(\text{Age}_x, \text{by PensionBand}) + \log(E_x^c) \quad (5.5)$$

Pension Band is implemented as a factor with three levels corresponding to *Pension Bands* 1, 2 and 3. Similar to section 5.3.1, this model includes a smooth function of *Age*, $f_1(\text{Age}_x)$, to capture the overall non-linear relationship between *Age* and mortality. However this model also includes a smooth function that allows the *Age* effect to vary across the three *Pension Bands*. Terms which were not significant at the 5% level were dropped from the models.

Tables 5.9 and 5.10 presents the results of fitting the models separately to the male and female data in Table 5.3 while Figures 5.9 and 5.10 presents the corresponding residuals plots following the removal of non-significant terms. In each case the models provide a good fit to the data with relatively simple smooth terms (as indicated by the low EDF).

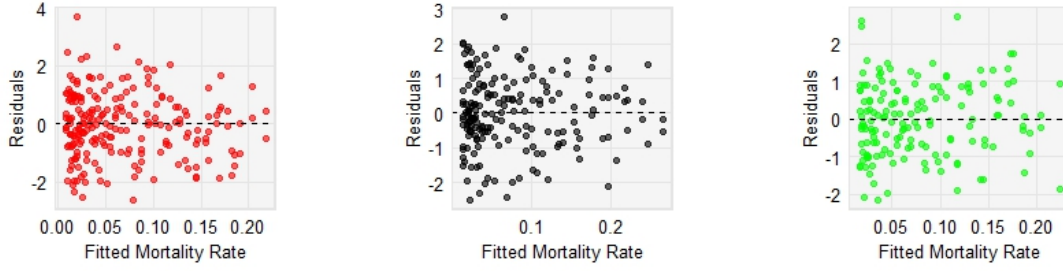
Age Group at Retirement	Age Range	Parameter	Males		Females	
			Estimate	p-value	Estimate	p-value
<55	55–85	B_0	-3.05815	0.00000	-3.67421	0.00000
		Pension Band 2	-0.23964	0.00000	-0.13257	0.00311
		Pension Band 3	-0.43963	0.00000	-0.24322	0.00000
55–59	60–85	B_0	-2.93790	0.00000	-3.54865	0.00000
		Pension Band 2	-0.19398	0.00000	-0.14669	0.00006
		Pension Band 3	-0.47319	0.00000	-0.37185	0.00000
60–65	65–85	B_0	-2.89396	0.00000	-3.43954	0.00000
		Pension Band 2	-0.14910	0.00000	-0.07360	0.16979
		Pension Band 3	-0.36176	0.00000	-0.21334	0.00077

Table 5.9: Parameter estimates and corresponding p-values, by *Age Group at Retirement* and gender fitted over the specified age ranges.

Age Group at Retirement	Age Range	Smooth Term	Males		Females	
			EDF	p-value	EDF	p-value
<55	55–85	$f_1(\text{Age}_x)$	3.090	0.00000	4.580	0.00000
		$f_2(\text{Age}_x, \text{by PensionBand1})$	1.968	0.01617	0.000	0.10500*
		$f_2(\text{Age}_x, \text{by PensionBand2})$	0.002	0.01898	0.000	0.88900*
		$f_2(\text{Age}_x, \text{by PensionBand3})$	0.899	0.00533	0.000	0.89100*
55–59	60–85	$f_1(\text{Age}_x)$	2.975	0.00000	1.906	0.00000
		$f_2(\text{Age}_x, \text{by PensionBand1})$	0.000	0.21360	0.223	0.22969
		$f_2(\text{Age}_x, \text{by PensionBand2})$	2.586	0.01730	0.000	0.33358
		$f_2(\text{Age}_x, \text{by PensionBand3})$	5.670	0.00000	2.679	0.00186
60–65	65–85	$f_1(\text{Age}_x)$	1.274	0.00000	1.166	0.00000
		$f_2(\text{Age}_x, \text{by PensionBand1})$	0.000	0.94720	0.596	0.02870
		$f_2(\text{Age}_x, \text{by PensionBand2})$	0.000	0.36970	0.000	0.61730
		$f_2(\text{Age}_x, \text{by PensionBand3})$	3.726	0.00350	0.000	0.55450

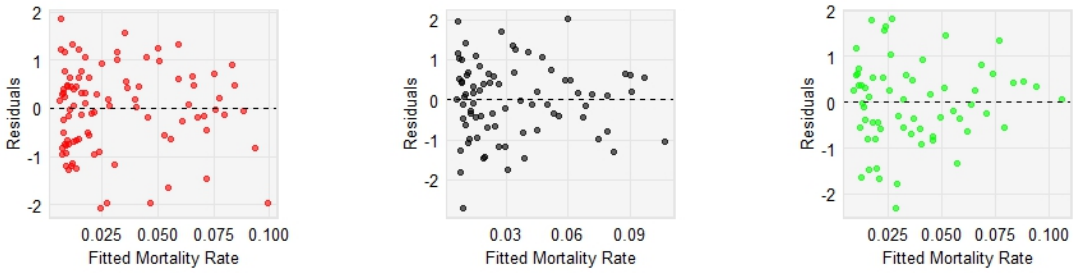
Table 5.10: EDF and p-values for each of the smooth terms, shown by *Age Group at Retirement* and gender fitted over specified age ranges.

* The smooth term ($f_2(\text{Age}_x, \text{by Industry})$) was not significant at the 5% level for females who retired before age 55 and was therefore dropped from the model.



(a) Retirement age < 55 (b) Retirement age 55 - 59 (c) Retirement age 60 - 65

Figure 5.9: Male residual plot from GAMs containing smooth functions of *Age* and *Pension Band*.



(a) Retirement age < 55 (b) Retirement age 55 - 59 (c) Retirement age 60 - 65

Figure 5.10: Female residual plot from GAMs containing smooth functions of *Age* and *Pension Band*.

Table 5.11 presents the overall adjusted R^2 values for each model and indicate an overall good model fit across both genders.

Age Group at Retirement	Adj R^2	
	Males	Females
<55	90.3%	85.5%
55-59	94.9%	95.6%
60-65	99.1%	94.0%

Table 5.11: Adjusted R^2 values from GAM models including *Age* and *Pension Band*.

Figures 5.11 and 5.12 plot the resulting mortality rates for each model. Consistent with the ASDR analysis higher pension levels at retirement are consistently associated with lower mortality rates, regardless of the *Age Group at Retirement* or gender. Males tend to show a convergence of mortality rates at older ages across the *Pension Bands*. This is consistent with the analysis of the impact of *Pension Band* on the mortality of normal health retirement pensioners which also show a convergence in mortality by *Pension Band* at older ages (CMI (2024c)). At older ages, the impact of *Pension Band* reduces as other factors, such as advanced age and increased risk of poor health, become more significant. In general, female ill-health retirement pensioners do not show convergence by *Pension Band* at older ages.

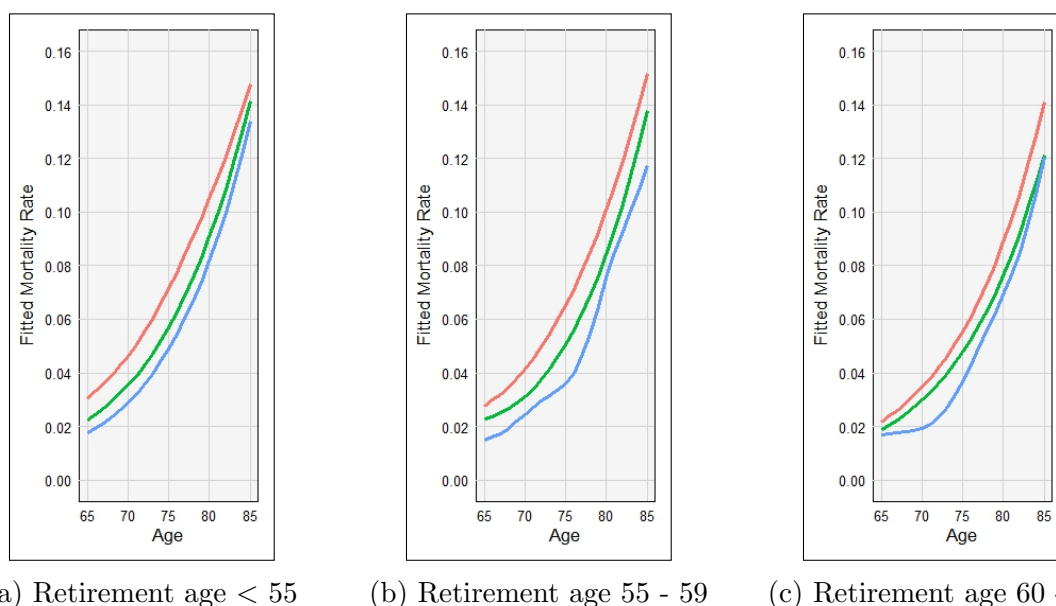


Figure 5.11: Male mortality rates by *Pension Band* and *Age Group at Retirement*. Pension Band 1 is represented by (—), Pension Band 2 by (—), and Pension Band 3 by (—).

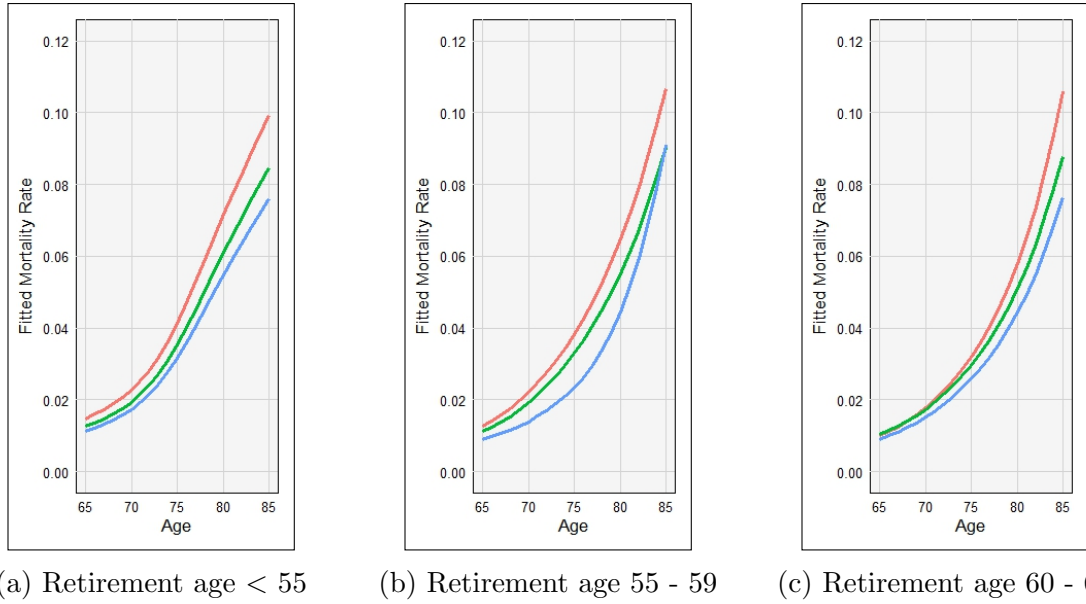


Figure 5.12: Female mortality rates by *Pension Band* and *Age Group at Retirement*. Pension Band 1 is represented by (—), Pension Band 2 by (—), and Pension Band 3 by (—).

To further examine the impact of pension band on the mortality of the ill-health pensioners, the 20-year survival probability from age 65 to 85 (i.e. ${}_{20}p_{65}$) was calculated for all groups. The results are summarised in Table 5.12:

	Males			Females		
	<55	55-59	60-65	<55	55-59	60-65
Pension Band 1	20%	22%	28%	38%	41%	45%
Pension Band 2	27%	30%	33%	44%	47%	49%
Pension Band 3	31%	37%	39%	48%	54%	54%

Table 5.12: The 20-year survival probability (from age 65 to 85) by *Pension Band* and *Age Group at Retirement* for males and females respectively.

The 20-year survival probability increases by both *Pension Band* and *Age Group at Retirement* for males and females. Additionally, for both genders, the survival probability gap between those retiring before age 55 and those retiring between ages 55-59 widens as the *Pension Band* increases, while the gap between those retiring at ages 55-59 and 60-65 decreases.

In general *Pension Band* band appears more important for modelling male ill health mortality than for females. This is consistent with the CMI analysis for

Normal Health pensioners as well as broader research findings (CMI (2024), Walczak, Wantoch-Rekowski, and Marczak (2021), and Chetty et al. (2016)). Furthermore, for both males and females, *Pension Band* has the greatest impact on those who retire at younger ages (i.e., under 55 and 55-59) compared to those who retire at old ages (i.e., 60-65).

5.4.4 Analysis of mortality by Age and Industry

Table 5.13 presents the ASDR's by *Industry Sector* for each *Age Group at Retirement* for males and females respectively for age range 65-85. The Public Sector & Local Authority industry grouping shows the lowest ASDR for females with relatively small differences by *Industry Sector* for males.

Age Group at Retirement	Males		Females	
	Public Sector & Local Authority	Private Sector	Public Sector & Local Authority	Private Sector
<55	5.2%	5.3%	4.2%	4.7%
55-59	5.1%	5.0%	4.0%	4.2%
60-65	5.0%	4.8%	3.7%	4.1%

Table 5.13: ASDR by *Age Group at Retirement* and *Industry Sector* for males and females aged 65-85.

Poisson GAMs were used to model the mortality of the ill-health retirement pensioners by *Age* and *Industry* across the three *Age Groups at Retirement* as follows:

$$\log(\mu'_x) = \beta_0 + \text{Industry} + f_1(\text{Age}_x) + f_2(\text{Age}_x, \text{by Industry}) + \log(E_x^c) \quad (5.6)$$

Industry Sector is implemented as a factor with two levels corresponding to the two industry groupings. Similar to section 5.4.1, this model includes a smooth function of *Age*, $f_1(\text{Age}_x)$, to capture the overall non-linear relationship between *Age* and mortality. However this model also includes a smooth function that allows the *Age* effect to vary by *Industry Sector*. Terms which were not significant at the 5% level were dropped from the models.

Tables 5.14 and 5.15 presents the results of fitting the models separately to

the male and female data in Table 5.4 while Figures 5.13 and 5.14 presents the corresponding residuals plots following the removal of non-significant terms. In each case the models provide a good fit to the data with relatively simple smooth terms (as indicated by the low EDF).

Age Group at Retirement	Age Range	Parameter	Males		Females	
			Estimate	p-value	Estimate	p-value
<55	55–85	B_0	-3.32148	0.00000	-3.83112	0.00000
		Private Sector	0.06038	0.00863	0.15390	0.00074
55–59	60–85	B_0	-3.16683	0.00000	-3.73341	0.00000
		Private Sector	0.04188	0.05910*	0.07693	0.10400*
60–65	65–85	B_0	-2.99274	0.00000	-3.74120	0.00000
		Private Sector	-0.00970	0.79700	0.21990	0.08180

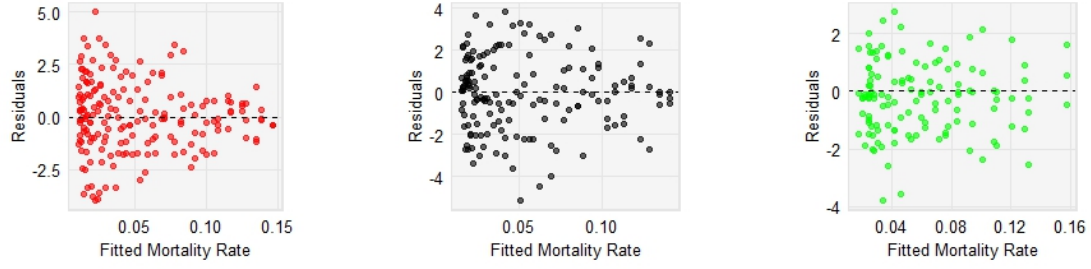
Table 5.14: Parameter estimates and p-values, by *Age Group at Retirement* and gender fitted over the specified age ranges.

Age Group at Retirement	Age Range	Smooth Term	Males		Females	
			EDF	p-value	EDF	p-value
<55	55–85	$f_1(\text{Age}_x)$	3.406	0.00000	4.611	0.00000
		$f_2(\text{Age}_x, \text{by PublicSector})$	0.000	0.86500**	0.000	0.96200**
		$f_2(\text{Age}_x, \text{by PrivateSector})$	0.000	0.88700**	0.000	0.97700**
55–59	60–85	$f_1(\text{Age}_x)$	4.013	0.00000	1.345	0.00000
		$f_2(\text{Age}_x, \text{by PublicSector})$	0.000	0.75000*	0.000	0.17900*
		$f_2(\text{Age}_x, \text{by PrivateSector})$	0.000	0.75900*	0.000	0.94300*
60–65	65–85	$f_1(\text{Age}_x)$	0.002	0.00000	0.001	0.00000
		$f_2(\text{Age}_x, \text{by PublicSector})$	1.820	0.00000	1.290	0.00000
		$f_2(\text{Age}_x, \text{by PrivateSector})$	4.383	0.00000	1.458	0.00000

Table 5.15: EDF and p-values for each of the smooth terms by *Age Group at Retirement* and gender, fitted over the specified age ranges.

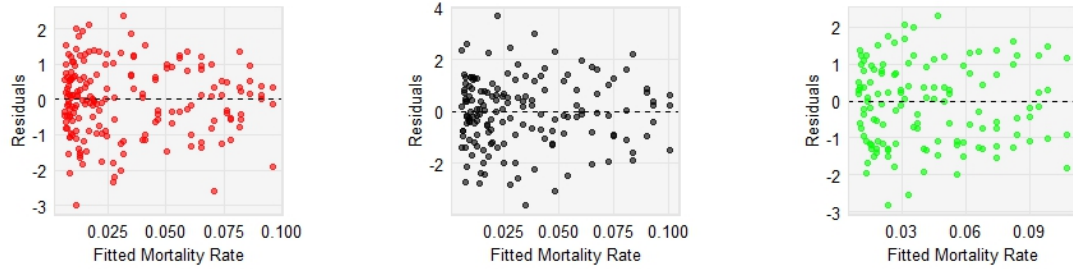
* The term 'Industry' was not significant at the level 5% in either the main term or smooth term for both males and females who retired between ages 55–59 and therefore these terms were removed from the model.

** The smooth term ($f_2(\text{Age}_x, \text{by Industry})$) was not significant at the 5% level for males and females who retired before age 55 and was therefore dropped from the model.



(a) Retirement age < 55 (b) Retirement age 55 - 59 (c) Retirement age 60 - 65

Figure 5.13: Male residual plot from GAM containing smooth functions of *Age* and *Industry*.



(a) Retirement age < 55 (b) Retirement age 55 - 59 (c) Retirement age 60 - 65

Figure 5.14: Female residual plot from GAM containing smooth functions of *Age* and *Industry*.

Table 5.16 presents the overall adjusted R^2 values for each model. For those who retired under the age of 55, these values are significantly higher for females compared to males whereas for those who retired between ages 60-65, the values are slightly higher for males than for females. Note: The *Industry* parameter was dropped from the models for both males and females who retired between ages 55-59.

Age Group at Retirement	Adj R^2	
	Males	Females
<55	75.3%	90.3%
55-59	82.5%	92.7%
60-65	97.8%	95.5%

Table 5.16: Adjusted R^2 values from GAM model including *Age* and *Industry*.

Figures 5.15 and 5.16 present the results of the fitted models for males and females. Similar to the results from the ASDR analysis for males, there is minimal difference in mortality rates between the Public Sector/Local Authority group and the Private Sector (in fact there is no difference for those who retired between ages 55-59). For females however, there is a difference for those who retired under age 55 and those who retired between ages 60-65. Consistent with the ASDR analysis, the mortality rate difference between industry groups is greater for females but not for males, suggesting that *Industry Sector* plays a more important role in explaining female mortality compared to male mortality.

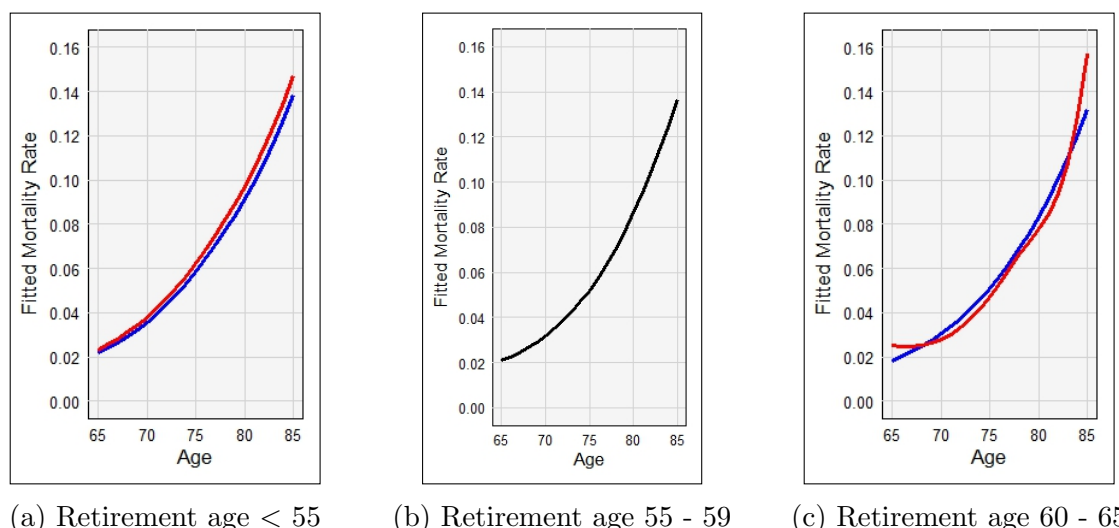


Figure 5.15: Male mortality rates by *Age Group at Retirement* and *Industry Sector* [Public Sector & Local Authority(—) and Private Sector (—)]. When there is no difference in mortality rates between *Industry Sector* this is represented by (—).

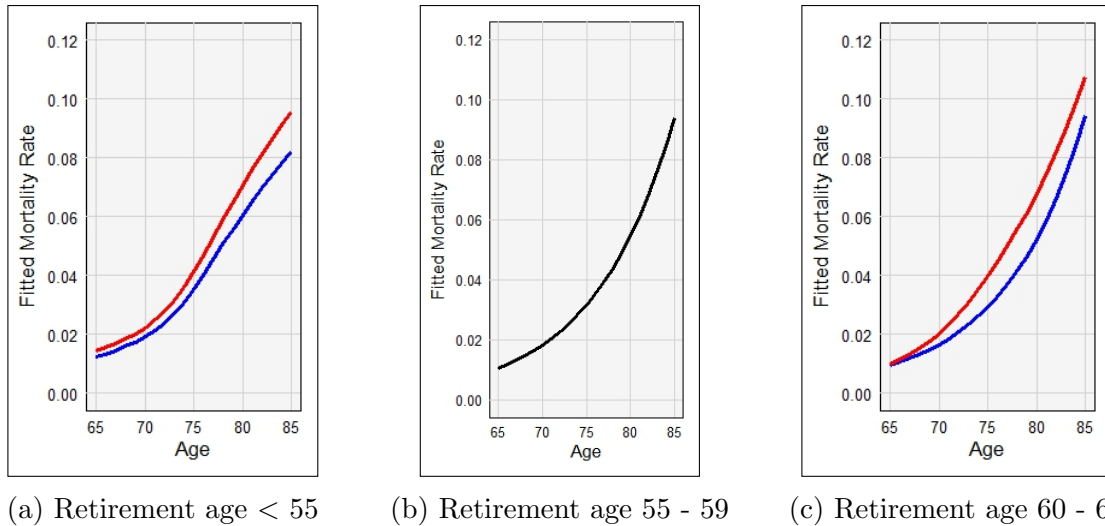


Figure 5.16: Female mortality rates by *Age Group at Retirement* and *Industry Sector* [Public Sector & Local Authority(—) and Private Sector (—)]. When there is no difference in mortality rates between *Industry Sector* this is represented by (—).

To further understand the impact of *Industry Sector*, the 20-year probability of surviving from age 65 to 85 was calculated for all groups. The probabilities are summarised in Table 5.17:

	Males			Females		
	<55	55-59	60-65	<55	55-59	60-65
Public Sector & Local Authority	23%	26%	27%	42%	43%	45%
Private Sector	21%	26%	27%	36%	43%	36%

Table 5.17: The 20-year survival probability (from age 65 to 85) by *Industry Sector* and *Age Group at Retirement* for males and females respectively

Table 5.17 above clearly illustrates the cumulative impact of *Industry Sector* on the 20-year *Industry Sector* survival probability between the ages of 65 and 85. For males, there is generally no difference in survival probabilities between the Public Sector & Local Authority group and the Private Sector. For females, the disparity is more significant, with a 6% difference for those who retired under age 55 and a 9% difference for those who retired between ages 60-65. Again, this suggests that *Industry Sector* plays a more important role in explaining female mortality rates compared to male mortality rates.

In general, *Industry Sector* appears to have the greatest impact on female ill-health retirement mortality compared to males.

5.5 Analysis of mortality by Age, Pension Band & Industry Sector combined

This section analyses the combined impact of *Age*, *Pension Band*, and *Industry Sector* for each of the three *Age Groups at Retirement*. This analysis is carried out for males only due to insufficient data for females in certain groupings (see Table 5.5).

The following poisson GAM was fitted to the male data in Table 5.5 for each of the three *Age Groups at Retirement*:

$$\begin{aligned}\log(\mu'_x) = & \beta_0 + \text{PensionBand} + f_1(\text{Age}_x) + f_2(\text{Age}_x, \text{by PensionBand}) \\ & + \text{IndustrySector} + f_3(\text{Age}_x, \text{by IndustrySector}) \\ & + \text{PensionBand:IndustrySector} + \log(E_x^c)\end{aligned}\tag{5.7}$$

As before, *Pension Band* and *Industry Sector* were implemented as factors and f_1, f_2, f_3 are smooth functions. Tables 5.18 and 5.19 presents the results of fitting the model to the male data while Figure 5.17 present the corresponding residual plots.

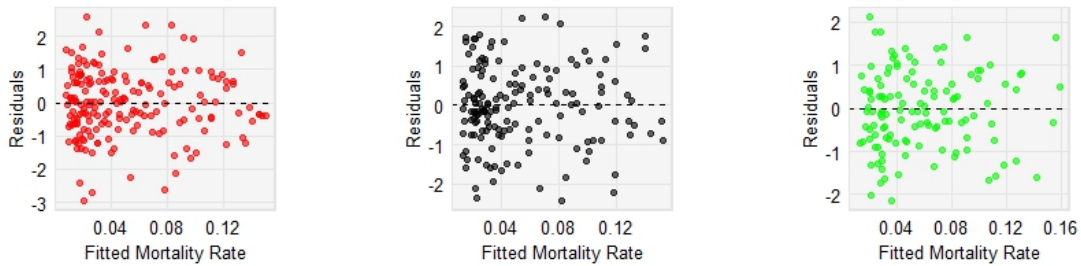
Age Group at Retirement	Fitted Age Range	Main Effect	Males	
			Estimate	p-value
<55	55-85	B_0	-3.04640	0.00000
		Pension Band 2	-0.27036	0.00000
		Pension Band 3	-0.59261	0.00000
		Private Sector	-0.03008	0.43400
		Pension Band 2: Private Sector	0.08025	0.15300
		Pension Band 3: Private Sector	0.30514	0.00000
55-59	60-85	B_0	-2.936245	0.00000
		Pension Band 2	-0.227217	0.00000
		Pension Band 3	-0.526681	0.00000
		Private Sector	-0.004191	0.90490
		Pension Band 2: Private Sector	0.088940	0.08790
		Pension Band 3: Private Sector	0.131575	0.01850
60-65	65-85	B_0	-2.88926	0.00000
		Pension Band 2	-0.17538	0.00000
		Pension Band 3	-0.43643	0.00000
		Private Sector	-0.03585	0.48230
		Pension Band 2: Private Sector	0.14502	0.04380
		Pension Band 3: Private Sector	0.21219	0.01630

Table 5.18: Estimates and p-values for the main effects, including intercept(B_0), *Pension Band*, *Industry Sector*, and the interaction between *Pension Band* and *Industry Sector* over the specified age ranges.

Age Group at Retirement	Fitted Age Range	Smooth Term	Males	
			EDF	p-value
<55	55-85	$f_1(\text{Age}_x)$	3.125	0.00000
		$f_2(\text{Age}_x, \text{by PensionBand1})$	1.910	0.02180
		$f_2(\text{Age}_x, \text{by PensionBand2})$	0.002	0.04850
		$f_2(\text{Age}_x, \text{by PensionBand3})$	0.814	0.02330
		$f_3(\text{Age}_x, \text{by Public Sector \& LA})$	0.000	0.21830*
		$f_3(\text{Age}_x, \text{by Private Sector})$	0.339	0.19660*
55-59	60-85	$f_1(\text{Age}_x)$	2.978	0.00000
		$f_2(\text{Age}_x, \text{by PensionBand1})$	0.000	0.20260
		$f_2(\text{Age}_x, \text{by PensionBand2})$	2.532	0.02380
		$f_2(\text{Age}_x, \text{by PensionBand3})$	5.665	0.00000
		$f_3(\text{Age}_x, \text{by Public Sector \& LA})$	0.000	0.67140*
		$f_3(\text{Age}_x, \text{by Private Sector})$	0.000	0.69030*
60-65	65-85	$f_1(\text{Age}_x)$	0.001	0.00000
		$f_2(\text{Age}_x, \text{by PensionBand1})$	0.000	0.92746
		$f_2(\text{Age}_x, \text{by PensionBand2})$	0.000	0.60155
		$f_2(\text{Age}_x, \text{by PensionBand3})$	2.815	0.00417
		$f_3(\text{Age}_x, \text{by Public Sector \& LA})$	1.472	0.00000
		$f_3(\text{Age}_x, \text{by Private Sector})$	4.213	0.00000

Table 5.19: EDF and p-values for each of the smooth terms.

* The smooth term containing 'Age' & 'Industry' (i.e., $f_3(\text{Age}_x, \text{by Industry})$) was not significant at the 5% level for males who retired under 55 and between ages 55-59 and therefore was subsequently dropped from model for both these retirement age groups.



(a) Retirement age < 55 (b) Retirement age 55 - 59 (c) Retirement age 60 - 65

Figure 5.17: Male residual plot from GAM containing smooth functions of *Age*, *Pension Band*, and *Industry* sector.

To access the impact of including both *Pension Band* and *Industry Sector*, the model excluding *Industry* (section 5.4.3, equation 5.5) was refitted to data in Table 5.5. Table 5.20 compares the fit of the model including and excluding *Industry*. The AIC and adjusted R^2 values change minimally for those who retired between the ages 55-59 and 60-65 indicating the inclusion of the *Industry* covariate provides limited benefit in improving the fit of the model., The only group with a modest improvement in the fit is for those who retired under age 55. For this group, the AIC decreased from 1,243 to 1,207, and the adjusted R^2 increased from 90.3% to 92.1% when compared to the model excluding *Industry*.

Model	Age Group at Retirement	Age Range Fitted	AIC	Adj R^2
Excluding Industry	<55	55-85	1,243	90.3%
Excluding Industry	55-59	60-85	1,075	94.9%
Excluding Industry	60-65	65-85	787	99.1%
Including Industry	<55	55-85	1,207	92.1%
Including Industry	55-59	60-85	1,068	95.1%
Including Industry	60-65	65-85	783	99.1%

Table 5.20: AIC and Adjusted R^2 values for models excluding and including *Industry* by *Age Group at Retirement*.

As shown in Table 5.20, only the under-55 *Age Group at Retirement* benefited from both *Pension Band* and *Industry Sector* being included in the model. Figures 5.18 and 5.19 present the results for individuals who retired under age 55, shown by *Pension Band* and *Industry Sector*. Pensioners in the Public Sector & Local authority show a greater gap in mortality rates between the pension bands (i.e great impact of pension band) relative to pensioners in the Private Sector. Figure 5.19 shows how mortality rates differ by *Industry Sector* across the three pension bands. There are generally minimal differences in mortality rates for those working in both *Industry Sectors* with a pension in band 1 or band 2. However, for those with a pension in band 3, the difference in mortality rates is much greater, with those working in the Private Sector having higher mortality rates than those working in the Public Sector & Local Authority.

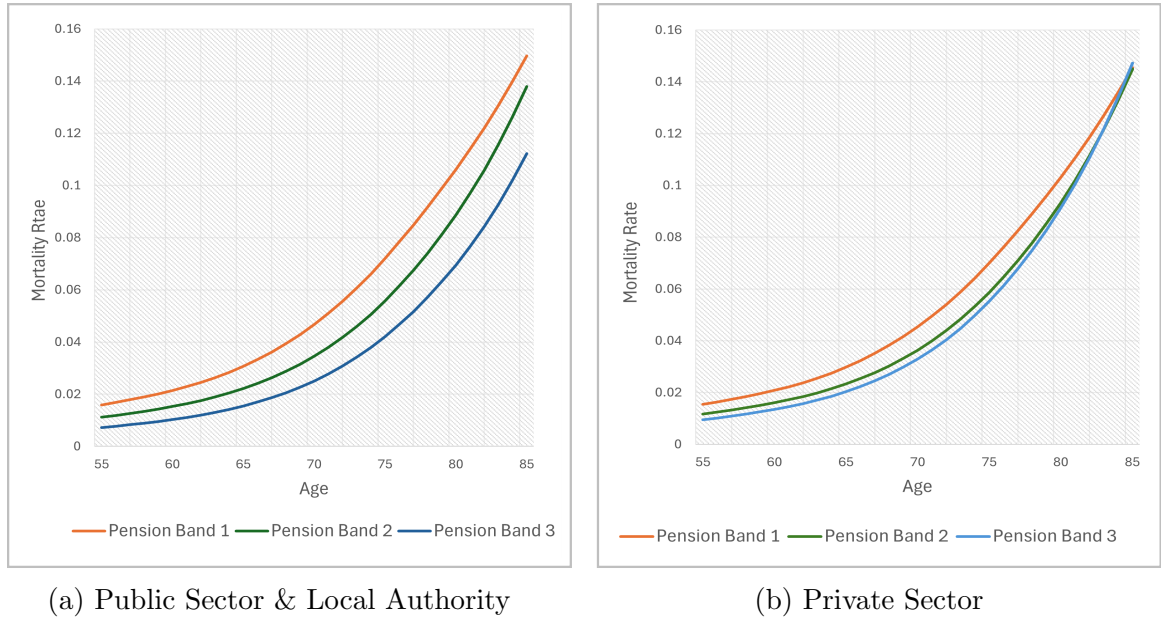


Figure 5.18: Male mortality rates for those who retired before age 55, for each *Pension Band* shown by *Industry Sector*.

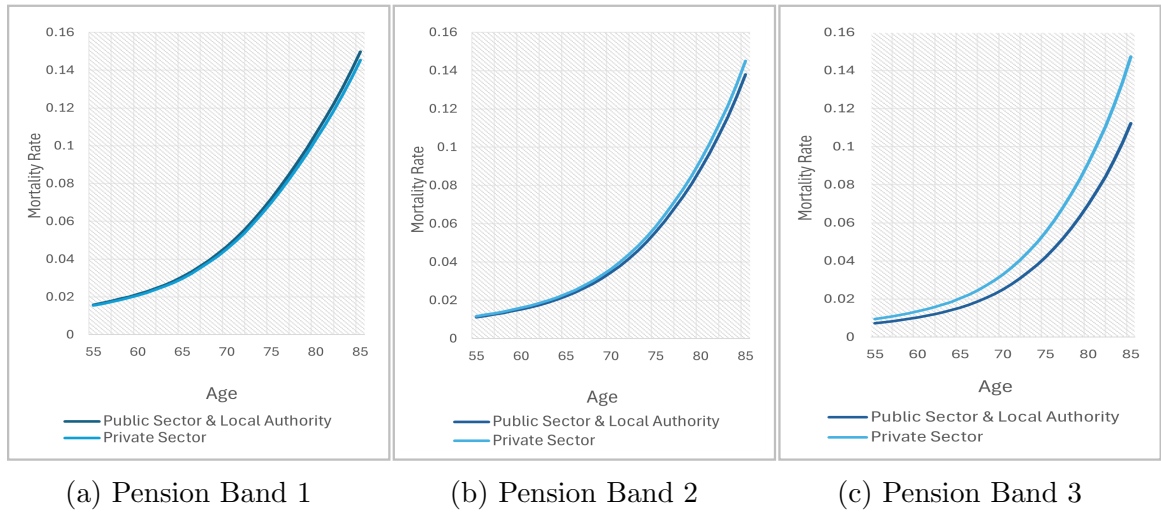


Figure 5.19: Male mortality rates for those who retired before age 55, for each *Industry Sector* shown by *Pension Band*.

Overall, when modelling the effects of *Pension Band* and *Industry Sector* together, the impact of *Pension Band* is more important for male mortality than the effect of *Industry sector*. However modelling both *Pension Band* and *Industry Sector* together should still be considered for males who retired under the age of 55.

5.6 Conclusion & Discussion

The analysis presented in this chapter show how mortality rates among those retiring on ill-health grounds vary across *Age Group at Retirement*, *Pension Band* and *Industry Sector*, with differences observed between males and females. Mortality rates generally decline with increasing retirement age, with individuals retiring before age 55, having higher mortality compared to older retirees. Across all *Age Groups at Retirement* and for both genders, higher *Pension Band's* at retirement are consistently associated with lower mortality rates. For males, mortality differences tend to converge at older ages across various pension bands, suggesting that *Pension Band* is a more important predictor of mortality among younger ages. Furthermore, *Pension Band* appears to play a more important role in modelling male ill-health retirement mortality than female ill health retirement mortality. While *Industry Sector* appears to have some influence on male mortality rates, it has a more pronounced effect on female mortality. The final part of the analysis in this chapter examined the combined effects of *Age*, *Pension Band*, and *Industry Sector* across the three *Age Groups at Retirement*, focusing on males due to limited female data in specific groupings. Although both *Pension* level and *Industry Sector* are relevant, *Pension Band* appears to have a stronger influence overall. However, for male ill-health retirements occurring before age 55, modelling by both *Pension Band* and *Industry Sector* should be considered.

The financial implications of the findings presented in this chapter are important. The analysis suggests that a uniform approach to pricing ill-health retirement annuities is no longer appropriate. Distinct mortality models should be considered to reflect the heterogeneity across different categories of ill-health retirees. Tables 5.21-5.27 in the Appendix to this chapter present life annuity rates for males and females at age 65, based on ultimate experience, assuming a maximum term of 20 years and a fixed interest rate of 3% per annum. These values are compared with those derived from the standard CMI S2 Ill-Health tables for males (S2IMA) and

females (S2IFA), which are weighted by pension amount, incorporate all experience (both ultimate and select) and are graduated by gender but are not differentiated by *Age Group at Retirement*, *Pension Band* or *Industry Sector*. The analysis shows considerable variations in annuity rates from these factors, highlighting the need to incorporate differentiated modelling approaches into the pricing of ill-health retirements. In particular, these findings reaffirm that a one size fits all approach is no longer appropriate for modelling ill-health annuities.

Understanding these factors is becoming increasingly important, as the number of individuals retiring due to ill-health is expected to rise. The likelihood of such an increase is driven by several factors, including workplace trends, demographic shifts, and evolving health conditions. Furthermore, the introduction of mandatory pension enrollment in several countries (e.g UK Nest Pension (2012) and Ireland's Auto Enrolment pension (2024)), has resulted in a higher number of employees joining pension schemes, which, in turn, leads to an increase in retirements on ill-health grounds. Additionally, as populations age and retirement ages increase, chronic health conditions are becoming more common among workers, often resulting in early retirements (Van Rijn et al. (2014)). Mental health issues, including stress and burnout, are now more frequently cited in ill-health pension claims (Salvagioni et al. (2017)), and the lasting effects of the Covid-19 pandemic, including long covid, have contributed to rising disability claims (Ford (2023), Miltimore (2023), Sutherland (2023), Pomeroy (2023)). Furthermore, advances in diagnostics and increased awareness of health conditions have expanded eligibility for disability pensions, with evolving policies facilitating easier access (Ercia (2021)). Healthier lifestyles promoted through public health campaigns and workplace benefits, such as remote working, may help to mitigate some of the anticipated growth in ill-health retirements by enabling employees with health challenges to remain in the workforce for longer (Gualano, Buttigieg, and Moscato (2023), Brassey and Ungerman (2023)). As pension schemes continue to evolve whether defined benefit plans or defined contribution arrangements (potentially involving the purchase of impaired annuities on

ill-health retirement), the importance of understanding ill-health mortality predictors including those analysed in this chapter will continue to grow.

Appendix: Evaluating Differences in Ill-Health Annuity Rates: Standard S2 Ill-Health Tables versus Customised Rates

5.6.1 Male Ill-Health Annuity Values

	CMI S2 Ill-Health Table (S2IMA)	<55	55–59	60–65
$\ddot{a}_{65:\overline{20} }$	11.65	11.16	11.51	11.77
% Difference	—	-4.2%	-1.2%	1.0%

Table 5.21: Male Ill-Health annuity factors and % differences (compared to the S2 Male Ill-Health table, S2IMA), by *Age Group at Retirement* (<55, 55–59, 60–65).

		<55			55–59			60–65		
	CMI S2 Il-Health Table (S2IMA)	PB1	PB2	PB3	PB1	PB2	PB3	PB1	PB2	PB3
$\ddot{a}_{65:\overline{20} }$	11.65	10.46	11.25	11.77	10.78	11.52	12.28	11.33	11.76	12.42
% Difference	—	-10.2%	-3.4%	1.0%	-7.5%	-1.1%	5.4%	-2.7%	0.9%	6.6%

Table 5.22: Male Ill-Health annuity factors and % Differences (compared to S2 Male Ill-health table S2IMA) by *Age Group at Retirement* (<55, 55–59, 60–65) and *Pension Band* (PB1, PB2, PB3).

		<55		55–59		60–65	
	CMI S2 Il-Health Table (S2IMA)	Public & LA	Private	Public & LA	Private	Public & LA	Private
$\ddot{a}_{65:\overline{20} }$	11.65	11.23	11.05	11.51	11.51	11.66	11.67
% Difference	—	-3.6%	-5.2%	-1.2%	-1.2%	0.1%	0.2%

Table 5.23: Male Ill-Health annuity factors and % Differences (compared to S2 Male Ill-health table S2IMA) by *Age Group at Retirement* (<55, 55–59, 60–65) and *Industry Sector* (Public Sector & Local Authority, Private Sector).

	CMI S2 Il-Health Table (S2IMA)	Public Sector & LA			Private Sector		
		PB1	PB2	PB3	PB1	PB2	PB3
$\ddot{a}_{65:\overline{20} }$	11.65	10.43	11.31	12.15	10.53	11.16	11.41
% Difference	—	-10.5%	-2.9%	4.3%	-9.6%	-4.2%	-2.1%

Table 5.24: Male Ill-Health annuity factors and % Differences (compared to S2 Male Ill-health table S2IMA) for those who retired <55 by *Industry Sector* (Public Sector & Local Authority, Private Sector) and Pension Band (PB1, PB2, PB3).

5.6.2 Female Ill-Health Annuity Values

	CMI S2 Il-Health Table (S2IFA)	<55	55–59	60–65
$\ddot{a}_{65:\overline{20} }$	12.88	12.60	12.85	12.99
% Difference	—	-2.2%	-0.2%	0.9%

Table 5.25: Female Ill-Health annuity factors and % Differences (compared to S2 Female Ill-health table S2IFA) by *Age Group at Retirement* (<55, 55–59, 60–65).

	CMI S2 Il-Health Table (S2IFA)	<55			55–59			60–65		
		PB1	PB2	PB3	PB1	PB2	PB3	PB1	PB2	PB3
$\ddot{a}_{65:\overline{20} }$	12.88	12.27	12.64	12.87	12.45	12.77	13.33	12.87	12.96	13.23
% Difference	—	-4.7%	-1.9%	-0.1%	-3.3%	-0.9%	3.5%	-0.1%	0.6%	2.7%

Table 5.26: Female Ill-Health annuity factors and % Differences (compared to S2 Female Ill-health table S2IFA) by *Age Group at Retirement* (<55, 55–59, 60–65) and *Pension Band* (PB1, PB2, PB3).

		<55		55–59		60–65	
	CMI S2 Ill-Health Table (S2IFA)	Public & LA	Private	Public & LA	Private	Public & LA	Private
$\ddot{a}_{65:\overline{20} }$	12.88	12.65	12.30	12.85	12.85	13.01	12.55
% Difference	—	-1.8%	-4.5%	-0.2%	-0.2%	1.0%	-2.6%

Table 5.27: Female Ill-Health annuity factors and % differences (relative to the S2 Female Ill-Health table, S2IFA), by *Age Group at Retirement* (<55, 55–59, 60–65) and *Industry Sector* (Public Sector & Local Authority, Private Sector).

Chapter 6

Mortality Effects of Widowhood

6.1 Introduction

The widowhood effect refers to the increase in mortality among individuals who have recently lost a spouse (Elwert and Christakis (2008)). Research consistently shows that widowed people, especially in the first few months to a year after the death of their partner, are more likely to die compared to their married peers (Stroebe, Schut, and Stroebe (2007), Shah et al. (2013), Espinosa and Evans (2008), and Moon et al. (2011)). This is commonly associated with a combination of emotional, psychological, social, and physiological factors (Carr and Utz (2001)). Factors such as socioeconomic status, health behaviors, and psychological resilience also play a role in influencing mortality differentials among widowed population (Shor et al. (2012) and Williams (2004)).

Models of the mortality experience of widow(er)s for actuarial applications should consider incorporating both reverse select mortality to allow for the widowhood effect and the subsequent ultimate mortality. Studies have shown that mortality risk can increase substantially within the first 6 to 12 months after losing a spouse, particularly for males (Sullivan and Fenelon (2014) and Moon et al. (2014)). Over time, this heightened risk tends to stabilise (ultimate period), although widowed individuals still have higher long-term mortality rates compared to their married counterparts. Davis (2023) found that men aged 65-59 have a 70% increased risk

of dying within the first year, while women face a 27% increased risk compared to their married counterparts. Other studies estimate that the long-term mortality risk associated with widowhood, compared to being married, to be around 15% after adjusting for various factors while the short-term impact during the initial months following bereavement shows a much higher risk, ranging from 50% to 90% (Schaefer, Quesenberry Jr, and Wi (1995), Elwert and Christakis (2008), and Martikainen and Valkonen (1996)).

This chapter analyses the impact of the Widowhood effect using the "S3" dependants dataset of the SAPS investigation of the Institute and Faculty of Actuaries, UK which covers the 8-year period 01 January 2009 - 31 December 2016 (CMI (2018)). This chapter is structured as follows:

- **Section 6.2** describes the dependant data used in the analysis.
- **Section 6.3** examines how the 1-year reverse select mortality rate compares to the ultimate mortality rate for male and female dependants and how these mortality rates vary with the age of widowhood.
- **Section 6.4** models the reverse select mortality for males and females using Generalised Additive models (GAMs).
- **Section 6.5** summaries the overall results.

6.2 Data

The "S3" data set from the Continuous Mortality Investigation (CMI) are derived from the Self-Administered Pension Schemes (SAPS) data in the UK for the period 01 January 2009 to 31 December 2016. Based on this data, the CMI has graduated a sets of thirty life tables namely the "S3" tables (CMI (2018)) and are categorised based on the following factors:

- Gender: Male, Female

- Retirement Type: Normal Health, Ill-health and Dependants
- Pension Amount Band: All, Light, Heavy, Very Heavy

The dependants dataset mainly refers to the widow(er)s of the normal-health and ill-health pensioners but also includes some dependant children particularly at younger ages. Companies often provide pensions to the children of deceased employees typically to age eighteen or twenty one or until they leave full time education and such pensions are typically administered by the company pension scheme under the category of dependants. As these tables are specifically tailored for self-administered pension schemes, they reflect the mortality experience of members which are likely to differ significantly from the general population, with pension scheme members typically experiencing lower mortality rates due to factors like higher income and better access to healthcare (Hardy and Waters (2018)).

Figure 6.3 presents the "S3" graduated rates for males and females over the age range 70-100 for All Pensioners (table PML/PFL) and Dependants (table DML/DFL) both on a lives basis. The mortality of the dependants is higher than that of all pensioners for both males and females with the gap being greater for males. For both males and females, the mortality rates for both groups generally coverage in the late 80's for females and in the early-mid 90's for males.

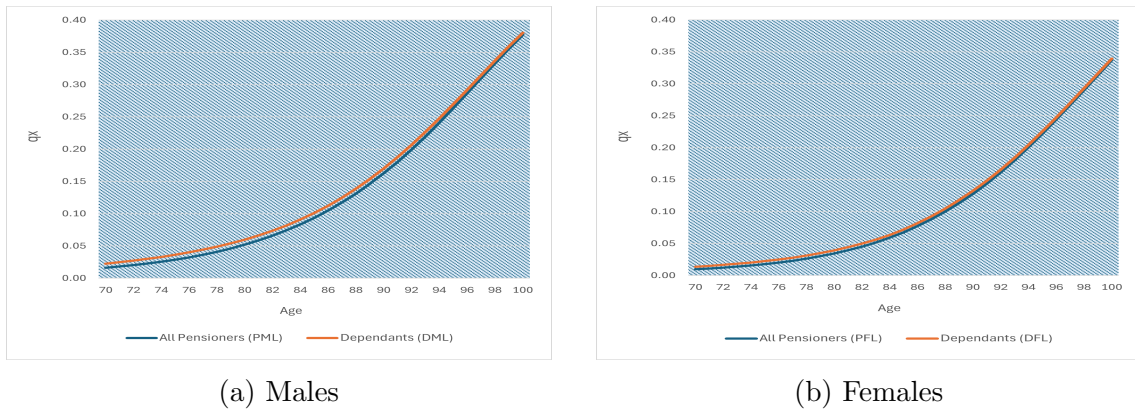


Figure 6.1: Graduated rates for males & females from the "S3" SAPS tables for All Pensioners (PML, PFL) and Dependants (DML, DFL) over the age range 70-100.

The CMI has kindly provided the dependant data underlying the "S3" dependant tables for this analysis. The following data was provided for each member: anonymous ID, date of birth, gender, pension start date, exit date, exit type, the start and end dates of the exposure period and the pension amount on the start and end dates. Dates of birth and start dates of pensions were anonymised to the 16th of each month. The pension start date was assumed to correspond to the date the dependant became widowed.

Table 6.1 presents the number of lives, the number of deaths, and the average age at widowhood for new widow(er)s aged over 25 during the exposure period (01 January 2009 – 31 December 2016), by gender. Females account for approximately 90% of the dependant data. The average age of widowhood was calculated by getting the difference between the date of birth and the pension start date for each individual.

	Male	Female	Total
Number of Lives	200,260	1,633,178	1,833,438
Number of Deaths	21,149	229,215	250,364
Average Age of Widowhood (New widows)	69.6	75.0	74.4

Table 6.1: Summary Statistics of the S3 Dependant dataset.

Figure 6.2 presents the number of lives by Age of Widowhood for new dependants during the exposure period (01/01/2009–31/12/2016), by gender. The distribution is slightly skewed to the left due to certain individuals such as children becoming dependents at very young ages.

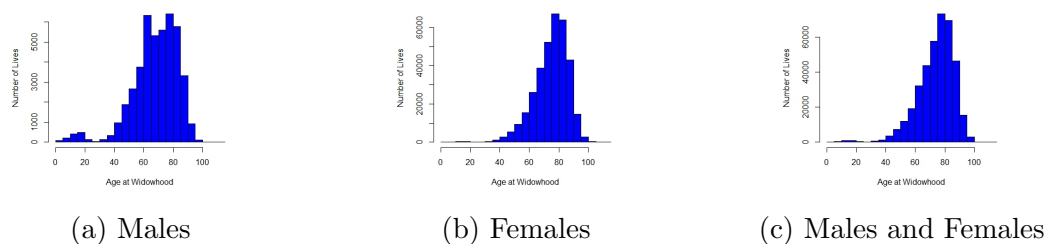


Figure 6.2: Number of lives who became dependants during the exposure period (01/01/2009–31/12/2016), shown by *Age at Widowhood* and gender.

Widowhood can severely impact the household income of the surviving spouse. Figure 6.2 presents the distribution of the annual 'Start Pension' amounts for new dependants who entered widowhood during the exposure period, by gender. Outliers such as those with yearly 'Start Pension' amounts exceeding £15,000 were excluded from the figure, as they represent only 1% of male cases and 5% of female cases. The median annual 'Start Pension' was £1,205 for males and £2,854 for females. This can be compared to the current annual UK basic State Pension of £11,973 for individuals receiving the new State Pension (Gov.UK (2025)). For context, Table 4.2 shows the UK poverty thresholds in 2022/2023.

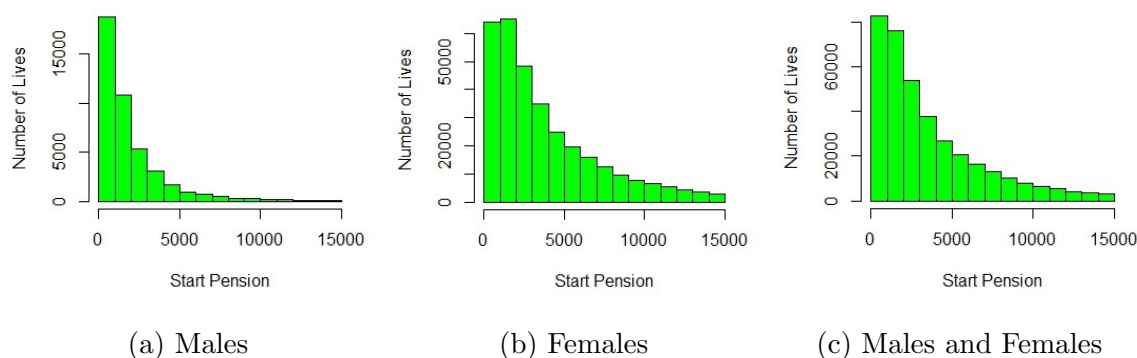


Figure 6.3: Distribution of 'Start Pension' amounts for new dependants who entered widowhood during the exposure period (01/01/2009–31/12/2016), by gender.

Household Type	UK Poverty Line After Housing Costs (2022/23)	Destitution (2022)
Single Pensioner	£8,632	£4,940

Table 6.2: Yearly poverty thresholds in 2022/2023 for a single pensioner in the UK. (*Data Source: Trust for London (2024)*)

For the analysis the dependants were classified into four groups based on their age at widowhood: 50-59, 60-69, 70-79 and 80-89. Deaths and exposures for each of the four groups were calculated for males and females respectively. Exposures were calculated using the central exposed to risk method. Those who became widowed at ages under 50 and at ages 90+ were excluded from the analysis due to the small data volumes available. Tables 6.3 and 6.4 show the deaths and exposures for both

the 1-year reverse select and ultimate periods for males and females during the S3 exposure period.

Age Group at Widowhood	Males (Exposures/Deaths)	Females (Exposures/Deaths)
50-59	8,210 / 83	24,227 / 161
60-69	15,516 / 313	64,406 / 811
70-79	16,525 / 722	114,206 / 3,525
80-89	10,734 / 1,196	105,819 / 9,960

Table 6.3: Deaths & Exposures by *Age Group at Widowhood* for the 1-year reverse select period.

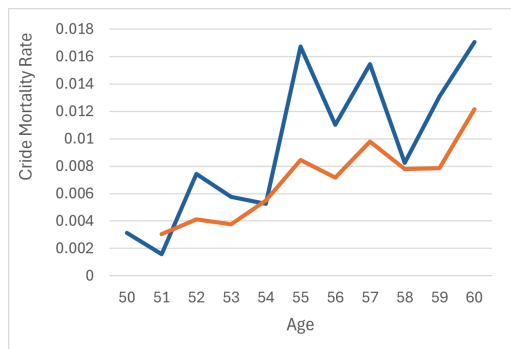
Age Group at Widowhood	Males (Exposures/Deaths)	Females (Exposures/Deaths)
50-59	31,986 / 268	96,955 / 546
60-69	59,258 / 1,106	257,718 / 2,987
70-79	56,278 / 2,769	441,309 / 14,230
80-89	28,422 / 3,577	359,597 / 37,278

Table 6.4: Deaths & Exposures by *Age Group at Widowhood* for the ultimate period.

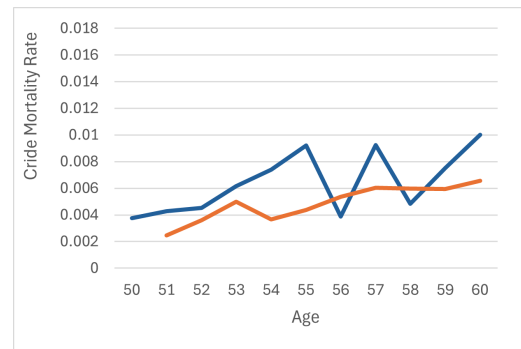
Note: *The exposures and deaths presented in Table 6.4 for the ultimate period are limited to the age range corresponding to the Age Group at Widowhood, rather than covering the entire ultimate period. This approach is used to allow a meaningful comparison with deaths and exposures for the 1-year reverse select period.*

6.3 Select and Ultimate mortality

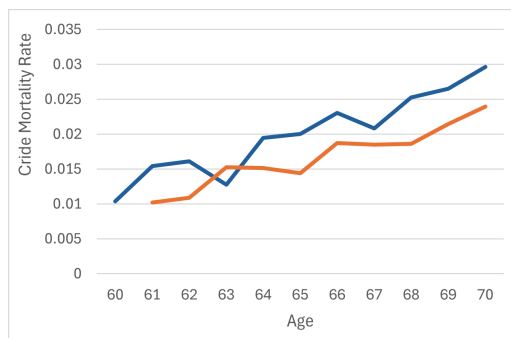
Figure 6.4 presents the 1-year reverse select and the corresponding ultimate crude mortality rates by age for males and females for the four *Age Groups at Widowhood*: 50-59, 60-69, 70-79, and 80-89. The difference between select and ultimate mortality rates can be interpreted as one measure of the widowhood effect. For both males and females and all *Age Groups at Widowhood*, the 1-year reverse select mortality rate is consistently higher than the corresponding ultimate mortality rate. This difference appears greater at younger ages for both males and females with the gap between the reverse select and ultimate mortality rates being larger for the 50-59 and 60-69 *Age Groups at Widowhood* compared to those who became widow(er)s at older groups. The widowhood effect (particularly for males) appears to diminish with age, i.e the difference between select and ultimate rates is smaller for older *Age Groups at Widowhood* compared to younger *Age Groups at Widowhood*.



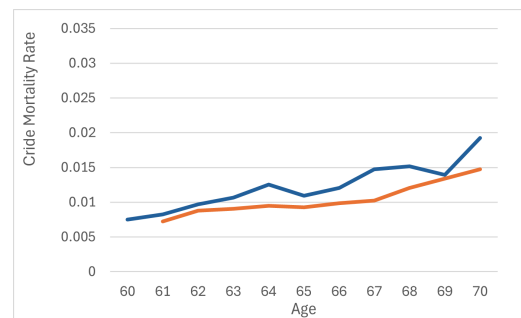
(a) Male 50-59



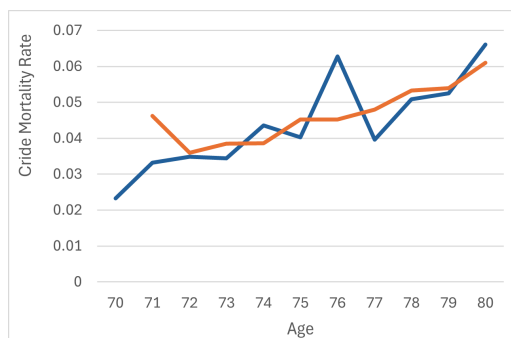
(b) Females 50-59



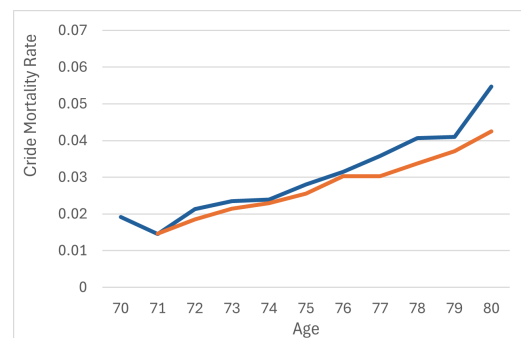
(c) Male 60-69



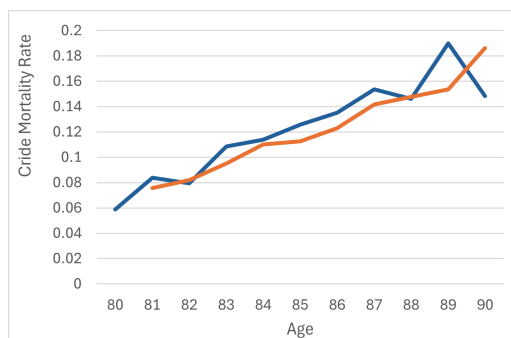
(d) Females 60-69



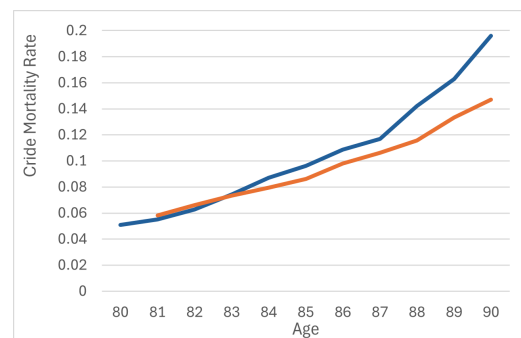
(e) Male 70-79



(f) Females 70-79



(g) Male 80-89



(h) Females 80-89

Figure 6.4: Crude mortality rates for 1-year reverse select (—) and ultimate (—) mortality rates by gender and Age Group at Widowhood: 50–59, 60–69, 70–79, and 80–89.

Figure 6.5 presents the corresponding Age Standardised Death Rates (ASDR's) for the 1-year reverse select and ultimate periods by *Age Group at Widowhood*. The ASDRs were calculated over the ten-year age ranges corresponding to each *Age Group at Widowhood*. These rates were standardised relative to the European Standard Population 2013 (ESP 2013) using the same methodology outlined in Section 2.2.3. The 1-year reverse select rate for both males and females consistently exceeds the corresponding ultimate rate across all *Age Groups at Widowhood*.

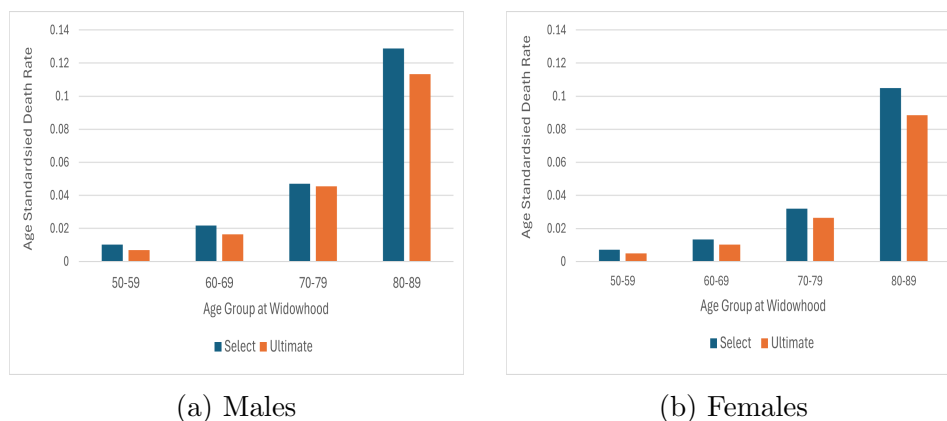


Figure 6.5: ASDRs for the 1-year reverse select period and ultimate period for males and females by *Age Group at Widowhood*: 50–59, 60–69, 70–79, and 80–89

Finally, Figure 6.6 presents the relative risk or the ratio of the 1-year reverse select to the ultimate ASDRs for both males and females across all four *Age Groups at Widowhood*. A relative risk level of "1" indicates that the risk is the same, while values above or below this level signify a difference in the risk of dying in the first year of widowhood compared to those with a longer duration of widowhood over the age ranges corresponding to the *Age Groups at Widowhood*. In most cases, there is a significantly higher risk of death during the first year of widowhood compared to those widowed for a longer period. For both males and females the risk is more pronounced at younger age groups compared to older *Age Groups at Widowhood*.

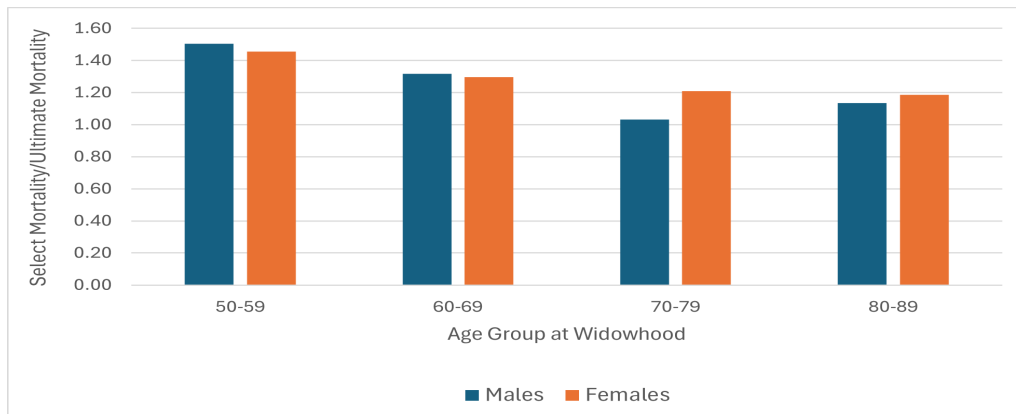


Figure 6.6: Select Mortality ASDR / Ultimate Mortality ASDR for males & females for *Age Group at Widowhood*: 0–59, 60–69, 70–79, and 80–89.

6.3.1 Modelling the Reverse Select Mortality

Figure 6.7(a) presents the 1-year crude reverse select mortality rates for males and females while Figure 6.7(b) presents the corresponding relative risk. The crude reverse select mortality rates for males and females at younger ages are quite volatile due to low data volumes (death counts in single digits). Looking at ages beyond 57, while the relative risk is still quite volatile it generally remains constant at c.1.5 up until age 77 and then declines until convergence between the male and female reverse select mortality rates is effectively reached in the late 80's. This is consistent with the convergence between male and female mortality generally seen at older ages.

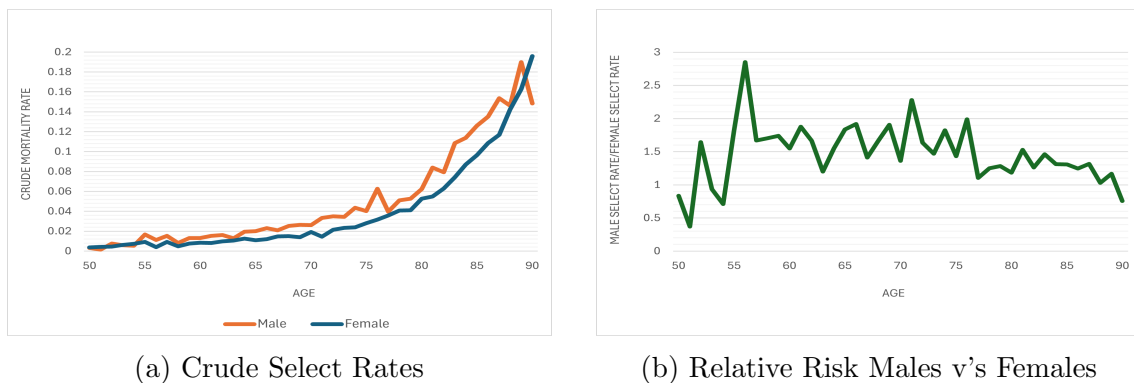


Figure 6.7: Crude 1-yr reverse select mortality rates for male & female dependants along with the corresponding relative risk for ages 50-90.

Using similar methodology as outlined in Section 2.2.4 to model the mortality of Ireland and Northern Ireland, Generalised Additive models (GAM's) were used to model the male and female reverse select mortality rates for the "S3" dependants. In particular it was decided to employ a difference smooth to jointly model the reverse select mortality. Deaths were assumed to follow a Poisson distribution and the following GAM was fitted to the reverse select data for males and females:

$$d_x \sim \text{Poisson}(E_x^c \mu'_x) \quad (6.1)$$

$$\log(\mu'_x) = \beta_0 + \text{Gender} + f_1(\text{Age}_x) + f_2(\text{Age}_x, \text{byGender} = \text{males}) + \log(E_x^c) \quad (6.2)$$

where d_x represents the number of deaths at age x and E_x^c represents the corresponding central exposed to risk. Gender is a 2-level factor variable with levels females (reference level) and males respectively. f_1 is a smooth function by Age for the reference level of the factor Gender i.e., f_1 is a smooth function by Age for the females. f_2 is implemented as a difference smooth function which models the mortality of males relative to that of females (the reference level of the factor Gender). Mortality rates for male dependants are inherently more volatile due to lower data volumes hence the choice of females as the reference level smooth given females represent 90% of the lives in the dataset. The GAM were fitted to data for ages 55-90 - data at ages under 55 and over 90 were excluded due to very low death counts at these ages.

The R library package "mgcv" (Wood (2025)) was used to carry out the modelling using thin plate regression splines as the smoothing functions (H2O (2025)). Table 6.5 presents the final fitted model while Figure 6.8 presents the corresponding residual plot. The adjusted R^2 value was 99.8%. For the final model, the parameter "k" was set to 20 for each smooth. As a check on the degrees of freedom chosen, the model was refitted with higher values of "k" but it had minimal impact on the effective degrees of freedom of the smooth functions. The p-values for all terms were highly significant (all zero to sixteen decimal places).

	Estimate(Std Error)
β_0	-3.45470 (0.01694)
Gender- males	0.29542 (0.02391)
Effective degrees of freedom for the smooth functions	
$f_1(\text{Age} - \text{females})$	3.690
$f_2(\text{Age} - \text{males})$	5.599

Table 6.5: Parameter values for the GAM for modelling male and female 1-year reverse select mortality.

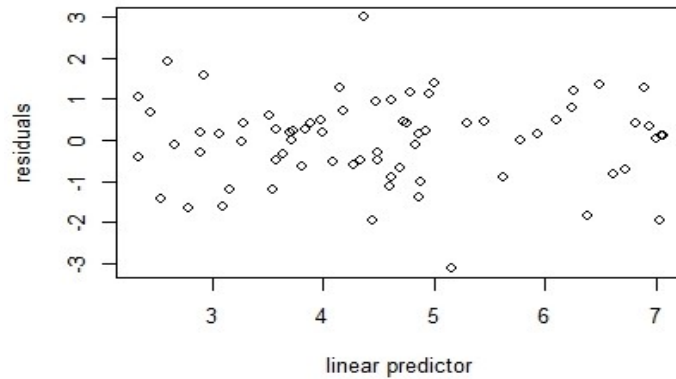


Figure 6.8: Residual plot for the GAM for modelling male and female 1-year reverse select mortality.

To illustrate the implementation of the smooth functions, Figure 6.9 presents the partial effects of the smooth functions on the mortality of the genders. The reference level smooth function for females reflects the expected increasing mortality pattern by age. The shape of the difference smooth for males is consistent with the pattern of the mortality gap between the genders described above - varying by age with the gap greatest at younger ages and falling at the oldest ages.

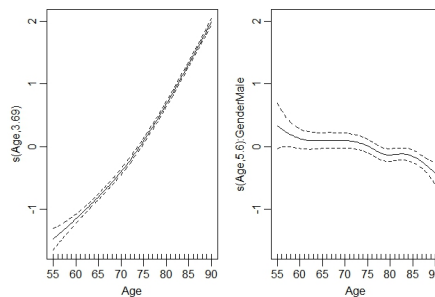


Figure 6.9: Partial effects of smooth functions for ages 55-90.

Figure 6.10 presents the final smoothed 1-year reverse select mortality rates for males and females for ages 55-90. The resulting mortality rates appear reasonable with a clear gap in mortality between the genders. Female 1-year reverse select mortality rates are consistently lower than the corresponding males rates with convergence between the genders at the oldest ages.

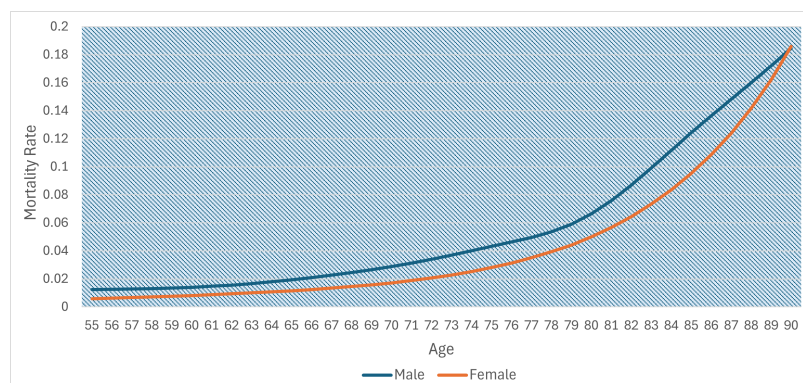


Figure 6.10: Smoothed 1-year reverse select mortality rates for males and females for ages 55-90.

6.4 Conclusion

Workforce trends have changed significantly in recent decades with an ever increasing number of females employed in the labour market and contributing to a pension. Therefore, the number of male dependants in pension schemes is expected to increase in the future. This trend highlights the growing importance of accurately modelling male dependant mortality both during the reverse select period and the ultimate period thereafter. By jointly modelling mortality for male and females dependants, smooth coherent 1-year reverse select mortality rates were successfully derived. The results show both males and females at younger ages experience a greater mortality impact from the loss of a spouse compared to older individuals. Additionally, the widowhood effect at younger ages is higher for males compared to females. At older ages, the impact of bereavement becomes less significant as other age-related and health-related factors dominate mortality risks, leading to convergence in reverse select rates for both genders. Furthermore, while at younger ages, the widowhood

effect is higher for males compared to females, at older ages the situation is reversed with females experiencing a greater widowhood effect.

With the gradual closure of defined benefit (DB) pension schemes to future accruals, the proportion of total liabilities represented by dependant benefits is expected to rise. This shift further emphasises the need for accurate and robust modelling of dependant mortality to ensure appropriate valuation of pension liabilities. These findings highlight the importance of ongoing research into dependant mortality, particularly in the context of changing demographics and pension scheme design.

Chapter 7

Conclusion

7.1 Findings

Actuaries require accurate models of current and future mortality for pricing and reserving/funding purposes. While Generalized Linear Models (GLMs) are widely used in actuarial work there has been relatively little use of Generalised Additive Models (GAMs). GAMs extend GLMs which model a linear relationship between a non-normal response y and predictors $x_1, \dots, x_n$ by allowing the linear predictor to include smooth functions of the covariates. This thesis demonstrated the use of GAMs in modelling mortality for a range of applications. GAMs provide a simple, flexible method of modelling mortality and it is hoped that they will become more widely used for for actuarial applications in the future.

As discussed in Chapter 2, Ireland experienced significant improvements in mortality since the turn of the century relative to both historic trends and the experience of other developed countries. However, there has been comparatively little analysis of Irish mortality to date – either population or insured lives mortality – primarily due to a lack of data for research. The lack of suitable life tables for actuarial purposes in Ireland is a serious issue facing the profession. This thesis has attempted to address this by investigating recent mortality trends in Ireland and Northern Ireland and proposing a method for graduating life tables for both regions through the joint modelling of their mortality experience. This approach enables the production

of more accurate and representative mortality estimates for both regions.

In line with other developed economies Ireland has an aging population. Seasonality of mortality is an issue for older populations, and this is particularly the case for Ireland which experiences relatively high levels of excess winter mortality. Milder winters due to climate change and improved influenza vaccines could significantly positively impact mortality rates at older ages in Ireland. Conversely, the emergence of Covid-19 and its impact on winter mortality could negate these improvements. Chapter 3 provides the first detailed analysis of seasonality on Irish mortality and used scenario analysis to assess the impact of changes in excess winter mortality on future mortality projections. This chapter provided a benchmark for future analysis of seasonality and climate change on Irish mortality.

The Covid-19 pandemic was one of the worst pandemics in history. As of April 2024, approximately 7 million confirmed deaths have been reported worldwide due to Covid-19 (Worldometer (2024)) with other research estimating the actual death toll may be significantly higher. Chapter 4 presented the results of a detailed analysis of the impact of the pandemic on Irish mortality in 2020 and 2021. This is the most detailed analysis of the impact of the pandemic on Irish mortality to date and provides a reference for future research on the pandemics' impact. Overall Ireland's relatively low excess mortality and proactive public health response suggest a strong performance in managing the pandemic during its first two years.

Finally, the CMI Self Administered Pension Scheme (SAPS) tables are widely used by Irish actuaries. As the volume of data collected by the CMI for the SAPS investigation continues to increase it is possible to carry out more detailed analysis of the factors affecting the mortality of pensioners. Typically, ill-health retirement pensioners and dependants form only a small part of the membership of occupational pension schemes and hence only (very) limited analysis of their mortality experience has been possible. However, using data from the CMI SAPS investigation, chapters 5 and 6 carried out a detailed investigation of the mortality these pensioner groups whose importance will increase in the future.

7.2 Limitations

7.2.1 Quality of Irish Population Mortality Data

Changes in death counts between datasets used in this thesis were primarily due to the effect of late death registrations which has become more significant in recent years. One of the main reasons for the delay in registering a death is due to pending coroners reports or inquests which determine the cause of death, an item that is needed to register a death. To address the challenge of timely, accurate death reporting (exacerbated during the pandemic years), the CSO has continued efforts to explore the use of alternative administrative data sources. Furthermore, recent legislative changes in Ireland (enacted 17 July 2024) have reduced the time limit for registering a death from 3 months to 28 days, introduced the option to register a death online for the first time and permits interim death certificates to be issued before the final cause of death is determined (Department of Social Protection (2024)). This legislation is another significant step towards improving the promptness of accurate death reporting in Ireland.

7.2.2 Lack of Irish Specific Industry Tables for Actuarial Applications

Due to limited Irish data, actuaries often turn to external sources such as the various studies carried out by the Continuous Mortality Investigation (CMI) in the UK. While these sources provide a useful benchmark, they may not fully reflect the unique characteristics of the Irish insured lives population. Recognising this gap, the Society of Actuaries in Ireland (SAI) has made efforts to develop mortality estimates tailored specifically to Irish insured lives. Initiatives such as the Self Administered Pension Scheme (SAPS) study (SAI (2020)), the Irish Insured Lives Mortality Investigation study (SAI (2019)) and the Term Assurance Experience Study (CMI (2025) (a joint collaboration between the SAI and CMI) have been

important steps in this direction. However, additional research support and funding are necessary to adequately resource the work needed.

As data availability and actuarial expertise continue to grow within Ireland, there is a strong case for expanding mortality and longevity research efforts, both for the insured population and the general population to ensure that mortality assumptions are relevant and locally appropriate.

7.3 Future work

Future work will focus on the following:

1. Irish Mortality updates: Regularly updating Irish mortality analysis to incorporate the most recent data and reflect any emerging trends. This includes considering the long-term impact of conditions such as long-covid, as well as global mortality patterns indicating rising mortality rates at younger ages, driven by factors such as substance abuse and mental health issues. Additionally, the increasing availability and use of GLP-1 medications (Zushin and Wu (2025) and Heile et al. (2018)) to manage chronic conditions such as diabetes and more recently obesity could significantly influence future Irish mortality improvements. Understanding and quantifying the impact of these developments will be essential for accurate modelling and forecasting of the Irish population.
2. Graduation of Irish life tables: The most recent Irish national Life Table (ILT17) are poor exhibiting unreasonable mortality patterns, volatile mortality rates and terminates at a relatively young ages. While the Central Statistics Office (CSO) has traditionally been responsible for the production of these tables, they are seeking professional actuarial input for the next iteration. Extensions to the Generalized Additive Models (GAMs) presented in this thesis should be considered to model the official Irish Life Tables. In particular, Generalized Additive Models for location, scale and shape could

potentially provide an improved modelling technique for the relatively small data volumes available for Irish mortality models.

3. Extension of the seasonal mortality analysis for Ireland: The CSO has recently released data linking monthly deaths and monthly temperature data for Ireland. The seasonal models of chapter 3 should be extended to allow for the effect of temperature on mortality. Such models would allow for an initial analysis of the impact of climate change on Irish mortality in the future.
4. Development of Irish specific insured lives and pensioners life tables: In recent years the Society of Actuaries in Ireland (SAI) has undertaken several investigations into the mortality experience of Irish pensioner and insured lives. The investigations typically performed high level, explorative analyses of the data, reporting results in an A/E format to allow timely reporting of the results. Future work would aim to comprehensively analyse and model these data sources using GAMs to develop Irish specific insured lives and pensioner life tables for actuarial applications.

Bibliography

- Abrahms, Briana, Neil H Carter, TJ Clark-Wolf, Kaitlyn M Gaynor, Erik Johansson, Alex McInturff, Anna C Nisi, Kasim Rafiq, and Leigh West (2023). “Climate change as a global amplifier of human–wildlife conflict”. In: *Nature Climate Change* 13.3, pp. 224–234.
- Aburto, José Manuel, Jonas Schöley, Ilya Kashnitsky, Luyin Zhang, Charles Rahal, Trifon I Missov, Melinda C Mills, Jennifer B Dowd, and Ridhi Kashyap (2022). “Quantifying impacts of the COVID-19 pandemic through life-expectancy losses: a population-level study of 29 countries”. In: *International journal of epidemiology* 51.1, pp. 63–74.
- Al-Rohaimi, Abdulmohsen H and Faisal Al Otaibi (2020). “Novel SARS-CoV-2 outbreak and COVID19 disease; a systemic review on the global pandemic”. In: *Genes & Diseases* 7.4, pp. 491–501.
- Andersen, Per Kragh, Ørnulf Borgan, Richard D. Gill, and Niels Keiding (1993). *Statistical Models Based on Counting Processes*. Springer. ISBN: 9780387945194.
- Argentieri, M Austin, Najaf Amin, Alejo J Nevado-Holgado, William Sproviero, Jennifer A Collister, Sarai M Kestra, Midas M Kuilman, Bigina NR Ginos, Mohsen Ghanbari, Aiden Doherty, et al. (2025). “Integrating the environmental and genetic architectures of aging and mortality”. In: *Nature Medicine*, pp. 1–10.
- Auto Enrolment* (2024). Accessed: 2024-12-03. URL: <https://www.citizensinformation.ie/en/money-and-tax/personal-finance/pensions/auto-enrolment/>.

-
- Ayuso, Mercedes, Jorge Bravo, Robert Holzmann, and Edward Palmer (2021). “Automatic Indexation of the Pension Age to Life Expectancy: When Policy Design Matters”. In: *Risks* 9(5), pp. 1–28. DOI: 10.3390/risks9050096.
- Ballester, Joan, Jean-Marie Robine, François Richard Herrmann, and Xavier Rodó (2011). “Long-term projections and acclimatization scenarios of temperature-related mortality in Europe”. In: *Nature Communications* 2.1, p. 358.
- Ballester, Joan, Xavier Rodó, Jean-Marie Robine, and François Richard Herrmann (2016). “European seasonal mortality and influenza incidence due to winter temperature variability”. In: *Nature Climate Change* 6.10, pp. 927–930.
- Balter, Anne G, Dorethe S Bjerre, and Malene Kallestrup-Lamb (2023). “The effect of marital status on life expectancy: Is cohabitation as protective as marriage?”. In: *Journal of Demographic Economics* 89.3, pp. 373–394.
- Bank, World (2020). *Public Service Delivery: Infrastructure and Institutional Challenges*. Washington, D.C.: World Bank Group. URL: <https://www.worldbank.org/>.
- Baraniuk, Chris (2021). *Covid-19: Why is Northern Ireland’s death rate so high?*
- Barrett, Alan, Seamus McGuinness, and Philip O’Connell (2024). *POPULATION PROJECTIONS, THE FLOW OF NEW HOUSEHOLDS AND STRUCTURAL HOUSING DEMAND*. RS190. Economic and Social Research Institute (ESRI). URL: <https://www.esri.ie/system/files/publications/RS190.pdf>.
- Basellini, Ugofilippo, Carlo Giovanni Camarda, and Heather Booth (2023). “Thirty years on: A review of the Lee–Carter method for forecasting mortality”. In: *International Journal of Forecasting* 39.3, pp. 1033–1049.
- Bauleo, Lisa, Stefania Massari, Claudio Gariazzo, Paola Michelozzi, Luca Dei Bardi, Nicolas Zengarini, Sara Maio, Massimo Stafoggia, Marina Davoli, Giovanni Viegi, et al. (2023). “Sector of Employment and Mortality: A Cohort Based on Different Administrative Archives”. In: *International Journal of Environmental Research and Public Health* 20.10, p. 5767.

-
- Bavel, Jay J. Van, Katherine Baicker, Paschaline S. Boggio, Valerio Capraro, Aleksandra Cichocka, Mina Cikara, Robb Willer, et al. (2020). “Using social and behavioural science to support COVID-19 pandemic response”. In: *Nature Human Behaviour* 4.5, pp. 460–471. DOI: 10.1038/s41562-020-0884-z. URL: <https://doi.org/10.1038/s41562-020-0884-z>.
- Bayraktar, Erhan, Moshe A Milevsky, S David Promislow, and Virginia R Young (2009). “Valuation of mortality risk via the instantaneous Sharpe ratio: applications to life annuities”. In: *Journal of Economic Dynamics and Control* 33.3, pp. 676–691.
- BBC (2020). *Coronavirus: First case confirmed in Republic of Ireland*. Accessed: 2025-03-27. URL: <https://www.bbc.com/news/world-europe-51693259>.
- Bennett, Kathleen E, Maeve Mullooly, Mark O’Loughlin, Margaret Fitzgerald, Joan O’Donnell, Lois O’Connor, Ajay Oza, and John Cuddihy (2021). “Underlying conditions and risk of hospitalisation, ICU admission and mortality among those with COVID-19 in Ireland: A national surveillance study”. In: *The Lancet Regional Health–Europe* 5.
- Boes, Stefan, Carla Sabariego, Jerome Bickenbach, and Gerold Stucki (2021). “How to capture the individual and societal impacts of syndemics: the lived experience of COVID-19”. In: *BMJ Global Health* 6.10, e006735.
- Bogdanović, Dragan, Zoran Milošević, Konstansa K Lazarević, Zana C Dolicanin, Dragan Ranelović, and Stefan D Bogdanović (2013). “The impact of the July 2007 heat wave on daily mortality in Belgrade, Serbia”. In: *Central European journal of public health* 21.3, pp. 140–145.
- Booth, Heather and Leonie Tickle (2008). “Mortality modelling and forecasting: A review of methods”. In: *Annals of actuarial science* 3.1-2, pp. 3–43.
- Boseley, Sarah (Dec. 24, 2008). *Flu outbreak is worst for eight years*. Accessed: 2025-04-14. URL: <https://www.theguardian.com/society/2008/dec/24/health-flu-outbreak>.

-
- Brassey Brad Herbig, Barbara Jeffery acqueline and Drew Ungerman (2023). *Reframing Employee Health: Moving Beyond Burnout to Holistic Health*. Accessed: 2024-12-03. URL: <https://www.mckinsey.com/mhi/our-insights/reframing-employee-health-moving-beyond-burnout-to-holistic-health>.
- Brown, C Hendricks (1993). “Analyzing preventive trials with generalized additive models”. In: *American Journal of Community Psychology* 21.5, pp. 635–664.
- BusinessPost (2005). *Tax breaks lead to doubling of nursing home beds*. Accessed: 2024-12-12. URL: <https://www.businesspost.ie/legacy/tax-breaks-lead-to-doubling-of-nursing-home-beds/>.
- Cairns, Andrew JG, David Blake, Kevin Dowd, Guy D Coughlan, David Epstein, and Marwa Khalaf-Allah (2011a). “Mortality density forecasts: An analysis of six stochastic mortality models”. In: *Insurance: Mathematics and Economics* 48.3, pp. 355–367.
- Cairns, Andrew JG, David Blake, Kevin Dowd, Guy D Coughlan, David Epstein, Alen Ong, and Igor Balevich (2009). “A quantitative comparison of stochastic mortality models using data from England and Wales and the United States”. In: *North American Actuarial Journal* 13.1, pp. 1–35.
- Cairns, Andrew JG, David Blake, Kevin Dowd, Guy D Coughlan, and Marwa Khalaf-Allah (2011b). “Bayesian stochastic mortality modelling for two populations”. In: *ASTIN Bulletin: The Journal of the IAA* 41.1, pp. 29–59.
- Camarda, Chiara G (2008). “Mortality forecasting: a model comparison”. In: *International Journal of Forecasting* 24.4, pp. 645–663.
- Campbell, Annie (2017). “Excess winter mortality in England and Wales: 2016 to 2017 (provisional) and 2015 to 2016 (final)”. In: *Statistical Bulletin, Office for National Statistics*.
- Carlson, Colin J., Gregory F. Albery, Evan A. Eskew, et al. (2024). “Climate change is shifting the global infectious disease burden”. In: *Science* 384.6681. Accessed: 28 March 2025, p. 4500. DOI: 10.1126/science.adk4500. URL: <https://www.science.org/doi/10.1126/science.adk4500>.

-
- Carr, Deborah and Rebecca Utz (2001). “Late-life widowhood in the United States: New directions in research and theory”. In: *Ageing International* 27, pp. 65–88.
- Carr, Deborah and Rebecca L Utz (2020). “Families in later life: A decade in review”. In: *Journal of Marriage and Family* 82.1, pp. 346–363.
- Casadevall, Arturo et al. (2024). “Pandemics past, present, and future: progress and persistent risks”. In: *The Journal of Clinical Investigation* 134.7.
- Case, Anne and Angus Deaton (2020). “The Epidemic of Despair Among U.S. Adults”. In: *Proceedings of the National Academy of Sciences* 117.4, pp. 2081–2090.
- Casey, Eddie and Killian Carroll (2021). *The path for Ireland’s health budget*. Analytical Note Series No. 14. Irish Fiscal Advisory Council, Dublin. Available at: www.FiscalCouncil.ie.
- Cazelles, Bernard, Benjamin Nguyen-Van-Yen, Clara Champagne, and Catherine Comiskey (2021). “Dynamics of the COVID-19 epidemic in Ireland under mitigation”. In: *BMC Infectious Diseases* 21.1, p. 735.
- CBS (2023). *Life expectancy forecast for 65-year-olds: 20.89 years in 2029*. Accessed: 20 March 2024. URL: <https://www.cbs.nl/en-gb/news/2023/45/life-expectancy-forecast-for-65-year-olds-20-89-years-in-2029>.
- CBS Netherlands (2022). *Life Expectancy Forecast for 65-year-olds: 21.05 Years in 2028*. URL: <https://www.cbs.nl/en-gb/news/2022/45/life-expectancy-forecast-for-65-year-olds-21-05-years-in-2028>.
- Centers for Disease Control and Prevention (CDC) (1995). *Direct Standardization - Age Standardised Rate*. URL: <https://www.cdc.gov/nchs/data/statnt/statnt06rv.pdf>.
- Central Bank of Ireland (Dec. 2021). *Climate Change and Insurance Supervisory Expectations*. Accessed: 2025-07-21. URL: <https://www.centralbank.ie/docs/default-source/publications/supervision-notices/insurance-supervision-notice-on-climate-change.pdf>.

-
- Chetty, Raj, Michael Stepner, Sarah Abraham, Shelby Lin, Benjamin Scuderi, Nicholas Turner, Augustin Bergeron, and David Cutler (2016). “The association between income and life expectancy in the United States, 2001-2014”. In: *Jama* 315.16, pp. 1750–1766.
- Choi, Won-Young (2022). “Mortality rate of patients with COVID-19 based on underlying health conditions”. In: *Disaster medicine and public health preparedness* 16.6, pp. 2480–2485.
- Citizens Advice (2024). *Workplace pensions*. Accessed: 2024-11-26. URL: <https://www.citizensadvice.org.uk/debt-and-money/pensions/types-of-pension/workplace-pensions>.
- Citizens Information (2024a). *Occupational Pensions*. Accessed: 2025-01-07. URL: <https://www.citizensinformation.ie/en/money-and-tax/personal-finance/pensions/occupational-pensions/>.
- (2024b). *Pensions*. Accessed: 2025-01-07. URL: <https://www.citizensinformation.ie/en/money-and-tax/personal-finance/pensions/>.
- CitizensInformation (2024). *Fuel Allowance*. Accessed: 2024-12-12. URL: <https://www.citizensinformation.ie/en/social-welfare/extra-social-welfare-benefits/fuel-allowance/>.
- Claussen, Bjørgulf and Odd Steffen Dalgard (2009). “Disability pensioning: the gender divide can be explained by occupation, income, mental distress and health”. In: *Scandinavian Journal of Public Health* 37.6, pp. 590–597.
- Clayton, David and Michael Hills (2013). *Statistical Models in Epidemiology*. 1st. Oxford University Press.
- Clinch, J Peter and John D Healy (2000). “Housing standards and excess winter mortality”. In: *Journal of Epidemiology & Community Health* 54.9, pp. 719–720.
- CMI (2001). *Continuous Mortality Investigation, Report No 20*. Tech. rep. U.K.: Institute and Faculty of Actuaries.
- (2008a). *Continuous Mortality Investigation, Working Paper No 34*. Working Paper. U.K.: Institute and Faculty of Actuaries.

-
- CMI (2008b). *Continuous Mortality Investigation, Working Paper No 35*. Working Paper. U.K.: Institute and Faculty of Actuaries.
- CMI (2013a). *Continuous Mortality Investigation, Working Paper No 65*. Working Paper. U.K.: Institute and Faculty of Actuaries.
- CMI (2013b). *Continuous Mortality Investigation, Working Paper No 66*. Working Paper. U.K.: Institute and Faculty of Actuaries.
- (2014). *Working Paper 71: Final “S2” Series of Mortality Tables*. Tech. rep. UK: Institute and Faculty of Actuaries. URL: <https://www.actuaries.org.uk>.
- (2015). *Working Paper 82: Seasonal Mortality Patterns and Their Impact on Mortality Forecasting*. Accessed: 2022-12-10. URL: <https://www.actuaries.org.uk/system/files/field/document/cmiwp82.pdf>.
- (2017). *CMI Working Paper 97- CMI Mortality Projections Model: CMI₂₀₁₆*. Tech. rep. UK: Institute and Faculty of Actuaries. URL: <https://www.actuaries.org.uk>.
- CMI (2017). *Graduation of the CMI Mortality Projections Model 2016 (CMI₂₀₁₆): Methodology*. Tech. rep. CMI Working Paper 91. Assumes deaths follow a Poisson distribution for graduation purposes. Institute and Faculty of Actuaries. URL: <https://www.actuaries.org.uk/documents/cmi-working-paper-91>.
- (2018). *Graduation of the CMI Mortality Projections Model 2017 (CMI₂₀₁₇): Methodology*. Tech. rep. CMI Working Paper 97. Uses Poisson regression to model deaths. Institute and Faculty of Actuaries. URL: <https://www.actuaries.org.uk/documents/cmi-working-paper-97>.
- CMI (2018). *Working Paper 113: Final “S3” Series Mortality Tables*. Tech. rep. UK: Institute and Faculty of Actuaries. URL: <https://www.actuaries.org.uk>.
- CMI (2021). *CMI 2020 Mortality Projections Model: Feedback and Initial Thoughts*. Tech. rep. CMI Working Paper 129. Continued use of Poisson-based models for mortality smoothing. Institute and Faculty of Actuaries. URL: <https://www.actuaries.org.uk/documents/cmi-working-paper-129>.

-
- CMI (2022). *Mortality Projections*. Accessed: 2025-04-01. URL: <https://www.actuaries.org.uk/learn-and-develop/continuous-mortality-investigation/cmi-investigations/mortality-projections>.
- (2023). *Calibration of the CMI Mortality Model for 2023 Projections*. Internal Report. Accessed: 2025-04-01. URL: <https://www.actuaries.org.uk/learn-and-develop/continuous-mortality-investigation/cmi-working-papers/mortality-projections/cmi-working-paper-189>.
- CMI (Feb. 2023). *Working paper 169: Mortality experience of pensioners for the period 2014 to 2021*. Tech. rep. Accessed: 2025-04-25. IFoA. URL: <https://www.actuaries.org.uk/learn-and-develop/continuous-mortality-investigation/cmi-working-papers/self-administered-pension-scheme-mortality/cmi-working-paper-169>.
- CMI (2024a). *CMI Says Death Rates in 2023 Lowest Since 2019*. Accessed: 2025-04-01. URL: <https://actuaries.org.uk/news-and-media-releases/media-releases-and-statements/2024/jan/17-jan-24-cmi-says-death-rates-in-2023-lowest-since-2019/>.
- CMI (2024b). *CMI Working Paper 195: Mortality experience of pensioners for the period 2016 to 2023*. Accessed: 2025-04-28. URL: <https://www.actuaries.org.uk/learn-and-develop/continuous-mortality-investigation/cmi-working-papers/self-administered-pension-scheme-mortality/cmi-working-paper-195>.
- (2024c). *Final S4 Series Mortality Rates*. Accessed: 2025-04-09. URL: <https://www.actuaries.org.uk/documents/final-s4-series-mortality-rates>.
- CMI (2024). *Working paper 194 - Multi-factor analysis of the mortality experience of pensioners for 2015 to 2022*. Tech. rep. 194. Accessed: 2025-04-24. IFoA. URL: <https://www.actuaries.org.uk/learn-and-develop/continuous-mortality-investigation/cmi-working-papers/self-administered-pension-scheme-mortality/cmi-working-paper-194>.

-
- CMI, SAI (2025). *Working Paper 199: Experience of term assurances in Ireland 2015-2021*. Tech. rep. UK: Institute and Faculty of Actuaries. URL: <https://www.actuaries.org.uk/learn-and-develop/continuous-mortality-investigation/cmi-working-papers/assurances/cmi-working-paper-199>.
- Commission, European (2024). *2024 Ageing Report: Country Fiche - Ireland*. Accessed: 2025-04-01. URL: https://economy-finance.ec.europa.eu/document/download/22478534-44d6-402b-b44a-feff07fa0e6b_en?filename=2024-ageing-report-country-fiche-Ireland.pdf.
- Continuous Mortality Investigation (2020). *Working Paper 129 – Frequently Asked Questions (FAQs)*. Institute and Faculty of Actuaries, UK. URL: <https://www.actuaries.org.uk/learn-and-develop/continuous-mortality-investigation/cmi-working-papers/mortality-projections/cmi-working-paper-129/mortality-improvements-and-cmi2019-frequently-asked-questions-faqs>.
- Contreras, Seba, Emil N Iftexhar, and Viola Priesemann (2023). “From emergency response to long-term management: the many faces of the endemic state of COVID-19”. In: *The Lancet Regional Health–Europe* 30.
- Cooke, Martin (2006). “Policy changes and the labour force participation of older workers: evidence from six countries”. In: *Canadian Journal on Aging/La revue canadienne du vieillissement* 25.4, pp. 387–400.
- Crosbie, Judith (2000). *Martin opens flu vaccine campaign by emphasising improvements*. The Office of Health Gain has said it hopes 65 percent of people in vulnerable groups will receive vaccination against the flu. URL: <https://www.irishtimes.com/news/martin-opens-flu-vaccine-campaign-by-emphasising-improvements-1.1102606> (visited on 04/04/2025).
- CS0 (2024). *SHA09 - Current Health Care Expenditure*. English. <https://data.gov.ie/dataset/sha09-current-health-care-expenditure>. Accessed: 2025-04-18. URL: <https://data.gov.ie/dataset/sha09-current-health-care-expenditure>.

-
- CSO (2008). *Population & Labour Force projections 2011-2041*. Accessed: 28 March 2025. URL: <https://www.cso.ie/en/media/csoie/releasespublications/documents/population/2008/background.pdf>.
- CSO (2013). *Population and Labour Force Projections 2016-2046*. Accessed: 2024-10-09. Central Statistics Office, Ireland. URL: https://www.cso.ie/en/media/csoie/releasespublications/documents/population/2013/poplabfor2016_2046.pdf.
- CSO (2015). *System of Health Accounts 2013*. English. <https://www.cso.ie/en/releasesandpublications/er/sha/systemofhealthaccounts2013/>. Accessed: 2025-04-18. URL: <https://www.cso.ie/en/releasesandpublications/er/sha/systemofhealthaccounts2013/>.
- CSO (2018). *Population and Labour Force Projections 2017-2051*. Accessed: 2024-10-09. Central Statistics Office, Ireland. URL: <https://www.cso.ie/en/releasesandpublications/ep/pplfp/populationandlabourforceprojections2017-2051/>.
- CSO (2020). *Information Note on the Implications of CoVid-19 on the Processing of Death Certificates*. Information Note. Central Statistics Office (CSO). URL: <https://www.cso.ie/en/releasesandpublications/in/vs/informationnoteontheimplications>
- CSO (2020). *Irish Life Tables No. 17, 2015-2017*. Accessed: 2024-10-08. URL: <https://www.cso.ie/en/releasesandpublications/er/ilt/irishlifetablesno172015-2017/>.
- CSO (2021). *Deaths Occurring – VSA08*. Accessed: 2021-12-11. URL: https://www.cso.ie/public/api.restful/PxStat.Data.Cube_API.ReadDataset/VSA08/XLSX/2007/en.
- CSO (2022). *Measuring Mortality Using Public Data Sources 2019-2021 (October 2019 – December 2021)*. Frontier Series Output. Central Statistics Office (CSO). URL: <https://www.cso.ie/en/releasesandpublications/fb/bmpds/measuringmortalityusingpublicdatasources2019-2021october2019-december2021/>.

-
- CSO (2024a). *Mortality Projections - PEA11*. Accessed: 20 March 2024. URL: <https://data.cso.ie/table/PEA11>.
- CSO (2024b). *PEA01 Dataset*. Accessed: 2024-12-04. URL: https://ws.cso.ie/public/api.restful/PxStat.Data.Cube_API.ReadDataset/PEA01/XLSX/2007/en.
- (2024c). *PEC23 Dataset*. Accessed: 2024-12-04. URL: https://ws.cso.ie/public/api.restful/PxStat.Data.Cube_API.ReadDataset/PEC23/XLSX/2007/en.
- CSO (2024d). *Population and Labour Force Projections 2023–2057: Mortality Assumptions*. Accessed: 2025-03-11. URL: <https://www.cso.ie/en/releasesandpublications/ep/p-plfp/populationandlabourforceprojections2023-2057/mortalityassumptions/>.
- CSO (2025). *Life Expectancy by Sex and Age, Yearly*. Accessed: 2025-03-11. URL: <https://data.cso.ie/table/FY001>.
- Currie, Ian D (2004). “Smoothing and forecasting mortality rates”. In: *Statistical Modelling* 4.4, pp. 279–298.
- Currie, Ian D. (2006). “Smoothing Mortality Rates Using P-splines and Generalized Additive Models”. In: *Scandinavian Actuarial Journal* 2006, pp. 213–231.
- Currie, Ian D., Marina Durban, and Paul H.C. Eilers (2004). “Smoothing and forecasting mortality rates with P-splines”. In: *Statistical Modelling* 4.4, pp. 279–298.
- Daly, Linda and Mary Hall (2025). “Mortality in Ireland and Northern Ireland 2000–2021 and the joint modelling of Irish and Northern Irish life tables”. In: *European Actuarial Journal*. ISSN: 2190-9741. DOI: 10.1007/s13385-025-00420-z. URL: <https://doi.org/10.1007/s13385-025-00420-z>.
- Daly, Linda, Mary Hall, Caroline Twomey, and Karl Murray (2024). *The level of excess mortality in Ireland during the Covid-19 pandemic 2020 & 2021*. Tech. rep. Society of Actuaries in Ireland. URL: https://web.actuaries.ie/sites/default/files/story/2024/05/SAI_CoVidReport_Final%20Issued.pdf.

-
- Davie, Gabrielle S, Michael G Baker, Simon Hales, and John B Carlin (2007). “Trends and determinants of excess winter mortality in New Zealand: 1980 to 2000”. In: *BMC public health* 7, pp. 1–9.
- Davis, Miriam (2023). “Mortality risk skyrockets in “young old” men after their spouse dies”. In: *Medscape*. Accessed: 2025-05-29. URL: <https://www.medscape.com/viewarticle/mortality-risk-skyrockets-young-old-men-2023a10005yp>.
- Department of Health, Ireland (2024). *Health in Ireland: Key Trends 2024*. Accessed: 24 March 2025. URL: <https://www.gov.ie/en/collection/f2e25-health-in-ireland-key-trends-2024/>.
- Department of Public Expenditure and Reform (2012). *Expenditure Report 2013*. Dublin: Department of Public Expenditure and Reform.
- Department of Social Protection (July 19, 2024). *Legislation to reform Ireland’s Civil Registration System enacted*. Accessed: 2025-05-30. URL: <https://www.gov.ie/en/press-release/a441f-legislation-to-reform-irelands-civil-registration-system-enacted/>.
- Dickson, David C. M., Mary R. Hardy, and Howard R. Waters (2013). *Actuarial Mathematics for Life Contingent Risks*. 2nd. Cambridge University Press. ISBN: 9781107044074.
- Djeundje, Viani B, Steven Haberman, Madhavi Bajekal, and Joseph Lu (2022). “The slowdown in mortality improvement rates 2011–2017: A multi-country analysis”. In: *European Actuarial Journal* 12.2, pp. 839–878.
- Dodd, Erengul, Jonathan J Forster, Jakub Bijak, and Peter WF Smith (2018). “Smoothing mortality data: the English life tables, 2010–2012”. In: *Journal of the Royal Statistical Society Series A: Statistics in Society* 181.3, pp. 717–735.
- DOH (2024). *Minister Butler announces €52.5 million funding for Meals on Wheels and Day Centres for Older People*. Accessed: 2024-12-12. URL: <https://www.gov.ie/en/press-release/121a2-minister-butler-announces-525-million-funding-for-meals-on-wheels-and-day-centres-for-older-people/>.

-
- Economic Co-operation, Organisation for and Development (OECD) (2012). *Strategic Public Infrastructure: Ensuring Economic Development and Sustainability*. Paris: OECD Publishing. URL: <https://www.oecd.org/>.
- EIOPA (2025). *European Insurance and Occupational Pensions Authority*. Accessed: 2025-03-21. URL: https://www.eiopa.europa.eu/index_en.
- Elwert, Felix and Nicholas A Christakis (2008). “The effect of widowhood on mortality by the causes of death of both spouses”. In: *American journal of public health* 98.11, pp. 2092–2098.
- Enchev, Vasil, Torsten Kleinow, and Andrew JG Cairns (2017). “Multi-population mortality models: fitting, forecasting and comparisons”. In: *Scandinavian Actuarial Journal* 2017.4, pp. 319–342.
- Epstein, Paul R (2001). “Climate change and emerging infectious diseases”. In: *Microbes and infection* 3.9, pp. 747–754.
- Ercia, Angelo (2021). “The impact of the Affordable Care Act on patient coverage and access to care: perspectives from FQHC administrators in Arizona, California and Texas”. In: *BMC health services research* 21, pp. 1–9.
- Espinosa, Javier and William N Evans (2008). “Heightened mortality after the death of a spouse: marriage protection or marriage selection?” In: *Journal of health economics* 27.5, pp. 1326–1342.
- Esteve, Albert, David S Reher, Rocío Treviño, Pilar Zuera, and Anna Turu (2020). “Living alone over the life course: Cross-national variations on an emerging issue”. In: *Population and Development Review* 46.1, pp. 169–189.
- EU (2009). *Solvency II Directive (2009/138/EC)*. Directive 2009/138/EC of the European Parliament and of the Council. Accessed: 2025-03-21. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0138>.
- European Central Bank (2023). *Pension Funds in the Euro Area - Third Quarter 2023*. Accessed: 2025-01-07. URL: <https://www.bde.es/f/webbe/GAP/Secciones/SalaPrensa/NotasInformativas/23/presbce2023-152en.pdf>.

-
- European Commission (Apr. 2015). *Commission Delegated Regulation (EU) 2015/35 of 10 October 2014 Supplementing Directive 2009/138/EC of the European Parliament and of the Council on the Taking-up and Pursuit of the Business of Insurance and Reinsurance (Solvency II)*. See Article 52 for the mortality risk submodule shock under the Standard Formula. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32015R0035>.
- (Apr. 2019). *The circumstances behind Ireland’s bailout in the late naughties*. Accessed: 2025-03-06. URL: https://ireland.representation.ec.europa.eu/news-and-events/news/circumstances-behind-irelands-bailout-late-naughties-2019-04-06_en.
- European Union (2015). *Regulation (EU) 2015/35: Supplementary Delegated Acts for Detailed Capital Calculations*. Regulation (EU) 2015/35 of the European Parliament and of the Council. Accessed: 2025-03-21. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32015R0035>.
- Eurostat (2013). *Revision of the European Standard Population: Report of Eurostat’s Task Force, 2013 Edition*. Luxembourg: Publications Office of the European Union. ISBN: 978-92-79-31094-2. DOI: 10.2785/11470. URL: <https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-ra-13-028>.
- (2019). *Divorce Indicators*. Accessed: 2022-12-10. URL: https://ec.europa.eu/eurostat/databrowser/view/demo_ndivind/default/table?lang=en.
- (2023). *Life table by age, sex and NUTS 2 Region*. (demo_r_mlife), Data downloaded November 2023. European Commission, Eurostat. URL: <https://ec.europa.eu/eurostat>.
- Faramarzi, Ahmad, Javad Javan-Noughabi, Sayed Ali Mousavi, Farshad Bahrami Asl, and Hamidreza Shabanikiya (2022). “Socioeconomic status and COVID-19-related cases and fatalities in the world: A cross-sectional ecological study”. In: *Health Science Reports* 5.3, e628.

-
- Feinglass, Joe, Suru Lin, Jason Thompson, Joseph Sudano, Dorothy Dunlop, Jing Song, and David W Baker (2007). “Baseline health, socioeconomic status, and 10-year mortality among older middle-aged Americans: findings from the Health and Retirement Study, 1992–2002”. In: *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 62.4, S209–S217.
- Feng, Cindy (2022). “Spatial-temporal generalized additive model for modeling COVID-19 mortality risk in Toronto, Canada”. In: *Spatial statistics* 49, p. 100526.
- Ferreira, Claudia, Marie-Françoise J Doursout, and Joselito S Balingit (2023). “Climate change and the risk of future pandemics”. In: *2000 Years of Pandemics: Past, Present, and Future*. Springer, pp. 341–368.
- Fitzpatrick, David (1980). “Irish emigration in the later nineteenth century”. In: *Irish Historical Studies* 22.86, pp. 126–143.
- Ford, Nicole D (2023). “Long COVID and significant activity limitation among adults, by age—United States, June 1–13, 2022, to June 7–19, 2023”. In: *MMWR. Morbidity and Mortality Weekly Report* 72.
- Fowler, Tom, Rosamund J Southgate, Thomas Waite, Ruth Harrell, Sari Kovats, Angie Bone, Yvonne Doyle, and Virginia Murray (2015). “Excess winter deaths in Europe: a multi-country descriptive analysis”. In: *The European Journal of Public Health* 25.2, pp. 339–345.
- Franke, Sebastian and Hill Kulu (2018). “Mortality differences by partnership status in England and Wales: the effect of living arrangements or health selection?” In: *European Journal of Population* 34, pp. 87–118.
- Fronteira, Inês, Mohsin Sidat, João Paulo Magalhães, Fernando Passos Cupertino de Barros, António Pedro Delgado, Tiago Correia, Cláudio Tadeu Daniel-Ribeiro, and Paulo Ferrinho (2021). “The SARS-CoV-2 pandemic: A syndemic perspective”. In: *One health* 12, p. 100228.
- Fuhrmann, Christopher (2010). “The effects of weather and climate on the seasonality of influenza: what we know and what we need to know”. In: *Geography Compass* 4.7, pp. 718–730.

-
- Gardner, John W and Jill S Sanborn (1990). “Years of potential life lost (YPLL)—what does it measure?” In: *Epidemiology* 1.4, pp. 322–329.
- Gavi, the Vaccine Alliance (2021). *New Study Suggests Risk of Extreme Pandemics Like COVID-19 Could Increase Threefold in Coming Decades*. Accessed: 2025-02-25. URL: <https://www.gavi.org/vaccineswork/new-study-suggests-risk-extreme-pandemics-covid-19-could-increase-threefold-coming>.
- Gorji, Shaghayegh and Ali Gorji (2021). “COVID-19 pandemic: the possible influence of the long-term ignorance about climate change”. In: *Environmental Science and Pollution Research* 28, pp. 15575–15579.
- Gov.UK (2025). *The new State Pension: What you’ll get*. Accessed: 2025-06-04. URL: <https://www.gov.uk/new-state-pension/what-youll-get>.
- Gráda, Cormac Ó and Kevin H O’Rourke (1997). “Migration as disaster relief: Lessons from the Great Irish Famine”. In: *European Review of Economic History* 1.1, pp. 3–25.
- Gregoriadis, Linus (Dec. 31, 1999). *Flu cases double in two weeks*. Accessed: 2025-04-14. URL: <https://www.theguardian.com/society/1999/dec/31/futureofthenhs.health>.
- Griffin, Niamh (2021). “Covid-19 vaccination rates: How does your county compare?” In: *Irish Examiner*. Accessed: 2025-03-27. URL: <https://www.irishexaminer.com/news/arid-40749309.html>.
- Gualano, Maria Rosaria, Stefan Buttigieg, and Umberto Moscato (2023). *Impact of digitalization on workers’ health and work-life balance*.
- Guinnane, Timothy W (1998). *The vanishing Irish: households, migration, and the rural economy in Ireland, 1850-1914*. Princeton University Press.
- H2O (2025). *GAM Thin Plate Regression Spline*. Accessed: 2025-06-03. URL: https://docs.h2o.ai/h2o/latest-stable/h2o-docs/data-science/thin_plate_gam.html.

-
- Haberman, Steven, Vladimir Kaishev, Pietro Millossovich, Andrés Villegas, Steven Baxter, Andrew Gaches, Sveinn Gunnlaugsson, and Mario Sison (2014). *Longevity basis risk: A methodology for assessing basis risk*.
- Haberman, Steven and Arthur Renshaw (2011). *Modelling Longevity Dynamics for Pensions and Annuity Business*. Cambridge University Press. ISBN: 9780521118255.
- Hajat, Shakoore (2017). “Health effects of milder winters: a review of evidence from the United Kingdom”. In: *Environmental Health* 16, pp. 15–22.
- Hall, M and N Friel (2011). “Mortality projections using generalized additive models with applications to annuity values for the Irish population”. In: *Annals of Actuarial Science* 5.1, pp. 19–32.
- Hall, Mary and Linda Daly (2016). “Modelling the reverse select and ultimate mortality experience of UK ill-health retirement occupational pension scheme members”. In: *Annals of Actuarial Science* 10.2, pp. 222–235.
- Hall, Mary and Rabia Naqvi (2023). “Seasonal mortality amongst UK occupational pension scheme members 2000–2016”. In: *British Actuarial Journal* 28, e11.
- Hall, Mary and Rabia Naqvi (June 2019). “Seasonal mortality at older ages in England and Wales 1993–2016”. In: *Health and Care Hot Topics*. London: IFoA.
- Hardy, M. A. and H. R. Waters (2018). “Pension Scheme Membership and Its Impact on Mortality: A Comparative Study”. In: *Journal of Pension Economics and Finance* 17.3, pp. 405–423. DOI: 10.1017/S1474747218000234.
- Hastie, Trevor and Robert Tibshirani (1986). “Generalized Additive Models”. In: *Statistical Science* 1.3, pp. 297–310. DOI: 10.1214/ss/1177013604.
- Haukenes, Inger, Sturla Gjesdal, Guri Rortveit, Trond Riise, and John Gunnar Mæland (2012). “Women’s higher likelihood of disability pension: the role of health, family and work. A 5–7 years follow-up of the Hordaland Health Study”. In: *BMC public health* 12, pp. 1–9.
- He, Yucong, William J Liu, Na Jia, Sol Richardson, and Cunrui Huang (2023). “Viral respiratory infections in a rapidly changing climate: the need to prepare for the next pandemic”. In: *EBioMedicine* 93.

-
- Health Information and Quality Authority (2022). *Descriptive Analysis of Covid-19 Epidemiological Indicators and Associated Contextual Factors in European Countries*. Health Information and Quality Authority. URL: <https://www.hiqa.ie/sites/default/files/2022-05/COVID-19-Epidemiological-analysis.pdf>.
- Healy, John D (2003). “Excess winter mortality in Europe: a cross country analysis identifying key risk factors”. In: *Journal of Epidemiology & Community Health* 57.10, pp. 784–789.
- Heide, Iris Van der, Rogier M van Rijn, Suzan JW Robroek, Alex Burdorf, and Karin I Proper (2013). “Is retirement good for your health? A systematic review of longitudinal studies”. In: *BMC public health* 13, pp. 1–11.
- Heile, Michael, Kathleen Wyne, Liana K Billings, Anthony Cannon, Yehuda Handelsman, and Michael Shannon (2018). “Cardiovascular outcomes with once-weekly GLP-1 RAs: clinical and economic implications”. In: *Journal of Managed Care & Specialty Pharmacy* 24.9-a Suppl, S42–S52.
- Hilton, Jason, Erengul Dodd, Jonathan J Forster, and Peter WF Smith (2019). “Projecting UK mortality by using Bayesian generalized additive models”. In: *Journal of the Royal Statistical Society Series C: Applied Statistics* 68.1, pp. 29–49.
- HMD (2019). *Population & Death Data by Age, Sex, Year, and Country*. Data downloaded August 2019. URL: <https://www.mortality.org>.
- HMD (2021). *Methods Protocol V6*. Accessed: 2021-03-05. URL: <https://www.mortality.org/File/GetDocument/Public/Docs/MethodsProtocolV6.pdf>.
- HMD (2024). *Life Expectancy Data*. Accessed: 2024-12-04. URL: <https://www.mortality.org/>.
- HMD (2025). *Human Mortality Database: Death & Population Data by Age, Sex, Year and Country*. Data downloaded February 2025. URL: <https://www.mortality.org>.

-
- Honekamp, Ivonne (2007). “PAYG in an ageing society: The case of Sweden versus Germany”. In: *Pensions: an international journal* 12.3, pp. 138–153.
- Horton, Richard (2020). “Offline: COVID-19 is not a pandemic”. In: *The lancet* 396.10255, p. 874.
- Hosmer, Clark L (1956). “Retirement and life expectancy”. In: *Journal of Gerontology* 11.2, pp. 204–204.
- House of Commons Work and Pensions Committee (2024). *The Future of the Pension System in the UK: Report of the Work and Pensions Committee*. Accessed: 2025-01-07. URL: <https://publications.parliament.uk/pa/cm5804/cmselect/cmworpen/144/report.html>.
- Housing, Local Government Department of and Heritage (2024a). *Housing Adaptation Grants for Older People and People with a Disability*. Accessed: 2024-12-12. URL: <https://www.gov.ie/en/service/6636c-housing-adaptation-grants-for-older-people-and-people-with-a-disability/>.
- (2024b). *Housing Aid for Older People Grant*. Accessed: 2024-12-12. URL: <https://www.gov.ie/en/service/1ca60-housing-aid-for-older-people-grant/>.
- Houston, Muiris (Oct. 15, 2001). *Fighting the flu*. Accessed: 2025-04-14. URL: <https://www.irishtimes.com/news/health/fighting-the-flu-1.332187>.
- HPSC (2020). *Epidemiology of COVID-19 in Ireland: Weekly Reports*. Accessed: 2025-03-26. URL: <https://www.hpsc.ie/a-z/respiratory/coronavirus/novelcoronavirus/surveillance/epidemiologyofcovid-19inirelandweeklyreports/>.
- HPSC (2021). *First Year of the COVID-19 Pandemic in Ireland*. Health Protection Surveillance Centre. URL: <https://www.hpsc.ie/a-z/respiratory/coronavirus/novelcoronavirus/surveillance/covid-19annualreports/First%20year%20of%20the%20COVID-19%20pandemic%20in%20Ireland.pdf>.
- HPSC (2024). *COVID-19 Deaths Reported in Ireland*. Accessed: 2024-10-08. URL: https://www.hpsc.ie/a-z/respiratory/coronavirus/novelcoronavirus/surveillance/covid-19deathsreportedinireland/COVID-19_Death_Report_Website_v1.8_02042024.pdf.

-
- HSE (2024). *Home Support Services*. Accessed: 2024-12-12. URL: <https://www.hse.ie/eng/home-support-services/>.
- Huang, Guogui, Fei Guo, Klaus F Zimmermann, Lihua Liu, Lucy Taksa, Zhiming Cheng, Massimiliano Tani, and Marika Franklin (2023). “The effect of the COVID-19 pandemic on life expectancy in 27 countries”. In: *Scientific Reports* 13.1, p. 8911.
- Hymans Robertson (2023). *Newsflash: First Look at the CMI 2023 Model Release*. Accessed: 2025-04-01. URL: https://www.hymans.co.uk/media/bjwc2kg3/newsflash_-_first_look_at_the_cmi_2023_model_release.pdf.
- Irish Association of Pension Funds (2018). *IAPF in the News - July 2018*. Accessed: 2025-01-07. URL: <https://www.iapf.ie/news/iapfinthenews/default.aspx?month=7&year=2018&id=53>.
- IrishIndependent (2012). *Reilly availed of lucrative tax breaks on nursing homes*. Accessed: 2024-12-12. URL: <https://www.independent.ie/irish-news/reilly-availed-of-lucrative-tax-breaks-on-nursing-homes/26874899.html>.
- Jones, Rodney P (2020). “Excess winter mortality and stalling international improvements in life expectancy and mortality rates”. In: *British Journal of Healthcare Management*, pp. 1–8.
- Jones, Rodney P and Andriy Ponomarenko (2022). “Trends in excess winter mortality (EWM) from 1900/01 to 2019/20—Evidence for a complex system of multiple long-term trends”. In: *International journal of environmental research and public health* 19.6, p. 3407.
- Journal, The (2024). *Births and Deaths in Ireland*. Accessed: 2024-03-24. URL: <https://www.thejournal.ie/births-and-deaths-ireland-6388684-May2024/#:~:text=There%20were%2054%2C678%20live%20births,20%25%20between%20then%20and%202023>.

-
- Kabir, Z and S O'Brien (2023). "Stalling life expectancy trends in Europe and decomposition analysis of mortality data". In: *European Journal of Public Health* 33.Supplement_2, ckad160–919.
- Kaplan, Robert M and Richard G Kronick (2006). "Marital status and longevity in the United States population". In: *Journal of Epidemiology & Community Health* 60.9, pp. 760–765.
- Kelly, David M, Danko Stamenic, Paul Mullane, Cliodhna Ní Bhuachalla, Robert Conway, Ciara Carroll, Lois O'Connor, Sarah M Doyle, Claire M Buckley, and Patricia M Kearney (2022). "COVID-19 pandemic in Ireland: epidemiology, public health restrictions and vaccination uptake". In: *HRB Open Research* 5, p. 28.
- Kenneally, Martin (2009). *Medical Cards, the 'Over 70s' and all that... out of the frying pan?* Accessed: 2024-04-02. URL: <https://www.ucc.ie/en/media/academic/centreforpolycystudies/MedicalCards%20the%E2%80%98980ver70s%E2%80%99.pdf>.
- Kim, Hyoun K and Patrick C McKenry (2002). "The relationship between marriage and psychological well-being: A longitudinal analysis". In: *Journal of family Issues* 23.8, pp. 885–911.
- King, George (1909). "On a New Method of Constructing and of Graduation Mortality and other Tables". In: *Journal of the Institute of Actuaries* 43.2, pp. 109–184.
- Kleinow, Torsten (2015). "A common age effect model for the mortality of multiple populations". In: *Insurance: Mathematics and Economics* 63, pp. 147–152.
- Kunst, AE, CWN Looman, and JP Mackenbach (1991). "The decline in winter excess mortality in the Netherlands". In: *International Journal of Epidemiology* 20.4, pp. 971–977.
- Laake, Knut and Jan Marcus Sverre (1996). "Winter excess mortality: a comparison between Norway and England plus Wales". In: *Age and ageing* 25.5, pp. 343–348.

-
- Lee, Ronald (2000). “The Lee-Carter method for forecasting mortality, with various extensions and applications”. In: *North American actuarial journal* 4.1, pp. 80–91.
- Lee, Ronald D and Lawrence R Carter (1992). “Modeling and forecasting US mortality”. In: *Journal of the American statistical association* 87.419, pp. 659–671.
- L&G (2016). *LGIM Foresight, September 2016*. Accessed: 21 March 2025. URL: https://am-cms.landg.com/globalassets/lgim/_document-library/insights/client-solutions/lgim-foresight-sep-2016-5c08.pdf.
- Li, Nan and Ronald Lee (2005). “Coherent mortality forecasts for a group of populations: An extension of the Lee-Carter method”. In: *Demography* 42, pp. 575–594.
- Lillard, Lee A and Linda J Waite (1995). “‘Til death do us part: Marital disruption and mortality”. In: *American journal of sociology* 100.5, pp. 1131–1156.
- Liu, Echu, Caress A Dean, and Keith T Elder (2023). *The impact of COVID-19 on vulnerable populations*.
- Liu, Xiaoyue, Jianping Huang, Changyu Li, Yingjie Zhao, Danfeng Wang, Zhongwei Huang, and Kehu Yang (2021). “The role of seasonality in the spread of COVID-19 pandemic”. In: *Environmental research* 195, p. 110874.
- Loughrey, John, Codd Mary, Conyard Karl, Parnian Jalili, Eamonn Gormley, and Patrick Wall (2023). “Impact of COVID-19 in Irish Nursing Homes: an assessment of variables associated with performance during first wave of the pandemic”. In: *Population Medicine* 5.Supplement.
- Macdonald, Angus S, Stephen J Richards, and Iain D Currie (2018). *Modelling mortality with actuarial applications*. Cambridge University Press.
- Mackenbach, Johan P, Irina Stirbu, Albert-Jan R Roskam, Maartje M Schaap, Gwenn Menvielle, Mall Leinsalu, and Anton E Kunst (2008). “Socioeconomic inequalities in health in 22 European countries”. In: *New England journal of medicine* 358.23, pp. 2468–2481.

-
- Macrotrends (2024). *Ireland GDP Growth Rate 1961-2024*. Accessed: 2024-12-04.
URL: <https://www.macrotrends.net/global-metrics/countries/IRL/%20Irlande/gdp-growth-rate>.
- Madaniyazi, Lina, Ben Armstrong, Aurelio Tobias, Malcolm N Mistry, Michelle L Bell, Aleš Urban, Jan Kyselý, Niilo Rytö, Ivana Cvijanovic, Chris Fook Sheng Ng, et al. (2024). “Seasonality of mortality under climate change: a multicountry projection study”. In: *The Lancet Planetary Health* 8.2, e86–e94.
- Madrigal, Ana M, Fiona E Matthews, DD Patel, AT Gaches, and SD Baxter (2011). “What longevity predictors should be allowed for when valuing pension scheme liabilities?” In: *British Actuarial Journal* 16.1, pp. 1–38.
- Majer, Istvan M, WJ Nusselder, JP Mackenbach, and AE Kunst (2011). “Socioeconomic inequalities in life and health expectancies around official retirement age in 10 Western-European countries”. In: *J Epidemiol Community Health* 65.11, pp. 972–979.
- Malik, Sid (2019). *Observations from Recent Regulatory Reviews*. Accessed: 2025-07-21. URL: <https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/letter/2019/observations-from-recent-regulatory-reviews.pdf>.
- Manzoli, Lamberto, Paolo Villari, Giovanni M Pirone, and Antonio Boccia (2007). “Marital status and mortality in the elderly: a systematic review and meta-analysis”. In: *Social science & medicine* 64.1, pp. 77–94.
- Marmot, Michael, Stephen Stansfeld, Chandra Patel, et al. (2020). *Health Inequalities in the UK: The Marmot Review 10 Years On*. Institute of Health Equity.
- Marmot, Michael G and Martin J Shipley (1996). “Do socioeconomic differences in mortality persist after retirement? 25 year follow up of civil servants from the first Whitehall study”. In: *Bmj* 313.7066, pp. 1177–1180.
- Martikainen, Pekka and Tapani Valkonen (1996). “Mortality after death of spouse in relation to duration of bereavement in Finland.” In: *Journal of Epidemiology & Community Health* 50.3, pp. 264–268.

-
- Mathieu, Edouard, Hannah Ritchie, Lucas Rod  s-Guirao, Cameron Appel, Charlie Giattino, Joe Hasell, Bobbie Macdonald, Saloni Dattani, Diana Beltekian, Esteban Ortiz-Ospina, and Max Roser (2020). *Covid-19 Stringency Index*. Accessed: September 20, 2024. URL: <https://ourworldindata.org/covid-stringency-index>.
- McCullagh, P. and J. A. Nelder (1989a). *Generalized Linear Models*. 2nd. Chapman and Hall/CRC.
- McCullagh, Peter and John A Nelder (1989b). “Monographs on statistics and applied probability”. In: *Generalized linear models* 37.
- McDaid, Olga, Mark J Hanly, Kathryn Richardson, Frank Kee, Rose Anne Kenny, and George M Savva (2013). “The effect of multiple chronic conditions on self-rated health, disability and quality of life among the older populations of Northern Ireland and the Republic of Ireland: a comparison of two nationally representative cross-sectional surveys”. In: *BMJ open* 3.6, e002571.
- McDonald, Tracey (2023). “Are we there yet? A guide to achieving endemic status for COVID-19 and variants”. In: *International Nursing Review* 70.1, pp. 1–6.
- McElhaney, Janet E (2008). “Influenza vaccination in the elderly: seeking new correlates of protection and improved vaccines”. In: *Aging health* 4.6, pp. 603–613.
- Mcgrath, Luke, Stephen Hynes, and John Mchale (2022). “Reassessing Ireland’s economic development through the lens of sustainable development”. In: *European Review of Economic History* 26.3, pp. 399–422.
- Medical Independent (2025). *Evaluating a pandemic five years on*. Accessed: 28 March 2025. URL: <https://www.medicalindependent.ie/in-the-news/news-features/evaluating-a-pandemic-five-years-on/>.
- Miltimore, Jonathan (2023). *Disability Claims Are Increasing at a Record Pace Under Biden. Why?* Accessed: 2024-12-03. URL: <https://fee.org/articles/disability-are-increasing-at-a-record-pace-under-biden-why/>.
- Moon, J Robin, M Maria Glymour, Anusha M Vable, Sze Y Liu, and SV Subramanian (2014). “Short-and long-term associations between widowhood and mor-

-
- tality in the United States: longitudinal analyses”. In: *Journal of Public Health* 36.3, pp. 382–389.
- Moon, J Robin, Naoki Kondo, M Maria Glymour, and SV Subramanian (2011). “Widowhood and mortality: a meta-analysis”. In: *PloS one* 6.8, e23465.
- Morgan, David, Paul Lukong, Philip Haywood, and Gabriel Di Paolantonio (2023). “Examining recent mortality trends: The impact of demographic change”. In.
- Müller, G., H. Jürges, and H. König (2006). “Using Generalized Additive Models to Model Mortality Rates in Actuarial Science”. In: *Insurance: Mathematics and Economics* 38.3, pp. 535–550.
- Munnell, Alicia H, Jean-Pierre Aubry, Geoffrey T Sanzenbacher, et al. (2015). *Does mortality differ between public and private sector workers?* Tech. rep. Centre of Retirement Research at Boston College.
- Murphy, Michael, Emily Grundy, and Stamatis Kalogirou (2007). “The increase in marital status differences in mortality up to the oldest age in seven European countries, 1990–99”. In: *Population studies* 61.3, pp. 287–298.
- Murtas, Rossella and Antonio Giampiero Russo (2019). “Effects of pollution, low temperature and influenza syndrome on the excess mortality risk in winter 2016–2017”. In: *BMC Public Health* 19, pp. 1–9.
- Nelder, John Ashworth and Robert WM Wedderburn (1972). “Generalized linear models”. In: *Journal of the Royal Statistical Society Series A: Statistics in Society* 135.3, pp. 370–384.
- NICE (Mar. 2015). *Excess winter deaths and illness and the health risks associated with cold homes*. Accessed: 2025-07-21. URL: <https://www.nice.org.uk/guidance/ng6>.
- Niraula, Anil (2019). *Public Employees Are Living Longer Than Previously Assumed, New Report Finds*. Online Commentary. Accessed: 2024-12-02. URL: <https://reason.org/commentary/public-employees-living-longer-than-previously-assumed-new-report/>.

-
- NISRA (2022). *Excess Mortality and COVID-19 Related Deaths to December 2022*. Accessed: 2024-10-08. URL: <https://www.nisra.gov.uk/publications/excess-mortality-covid-19-related-deaths-december-2022>.
- (2025a). *Suicide Statistics for Northern Ireland 2023*. Accessed May 2025. URL: https://www.nisra.gov.uk/files/nisra/publications/Suicide%20Statistics%20for%20NI%20Report%20-%202023%20-%20FINAL_2.pdf.
- (2025b). *Suicide Statistics for Northern Ireland 2023*. English. Report. Accessed: 2025-04-18. URL: https://www.nisra.gov.uk/files/nisra/publications/Suicide%20Statistics%20for%20NI%20Report%20-%202023%20-%20FINAL_2.pdf.
- Nolan, Anne, Sarah Barry, Sara Burke, and Steve Thomas (2014). *The Impact of the Financial Crisis on the Health System and Health in Ireland*. Accessed: 2024-12-05. URL: <https://www.esri.ie/system/files/publications/BKMNEXT289%20%281%29.pdf>.
- Ó Gráda, Cormac and Kevin Hjortshøj O'Rourke (2022). “The Irish economy during the century after partition”. In: *The Economic History Review* 75.2, pp. 336–370.
- O'Brien, Robert (Jan. 2024). *Public sector pension benefits valued at €176 billion*. Accessed: 2025-03-11. URL: <https://businessplus.ie/news/public-sector-pension-benefits/>.
- O'Connor, Rory C and Siobhan M O'Neill (2015). “Mental health and suicide risk in Northern Ireland: a legacy of the Troubles?” In: *The Lancet Psychiatry* 2.7, pp. 582–584.
- OECD (2023). *OECD Health Working Paper No. 163. Examining Recent Mortality Trends – The Impact of Demographic Change*. OECD. URL: [https://one.oecd.org/document/DELSA/HEA/WD/HWP\(2023\)15/en/pdf](https://one.oecd.org/document/DELSA/HEA/WD/HWP(2023)15/en/pdf).
- Office for National Statistics (2021). *Life Expectancy in the UK: 2021*. Accessed: 2025-03-21. URL: <https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/healthandlifeexpectancies>.

-
- Office for National Statistics (2022). *National Population Projections, Mortality Assumptions: 2020-based Interim*. URL: <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/methodologies/nationalpopulationprojections>
- Ofgem (Jan. 2022). *Warm Home Discount Annual Report: Scheme Year 10*. Tech. rep. Accessed: 2025-07-21. Ofgem. URL: <https://www.ofgem.gov.uk/publications/warm-home-discount-annual-report-scheme-year-10>.
- O'Neill, Siobhan and Rory C O'Connor (2020). "Suicide in Northern Ireland: Epidemiology, risk factors, and prevention". In: *The Lancet Psychiatry* 7.6, pp. 538–546.
- ONS (2017). *Excess Winter Mortality in England and Wales: 2016 to 2017 (Provisional) and 2015 to 2016 (Final)*. Accessed: 2021-12-05. URL: <https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/bulletins/excesswintermortalityinenglandandwales/2016to2017provisionalan>
- ONS (2020). *National Population Projections: Mortality Assumptions, 2020-based Interim*. Accessed: 20 March 2024. URL: <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/methodologies/nationalpopulationprojections>
- Pensions Authority (2024). *Defined Benefit Statistics*. Accessed: 2025-01-07. URL: https://pensionsauthority.ie/trustees_registered_administrators/funding_standard_and_funding_standard_reserve/defined_benefit_statistics_reports/.
- (2025). *IORP II Directive*. Accessed: 2025-03-24. URL: https://pensionsauthority.ie/trustees_registered_administrators/iorp_ii_directive/.
- Phillips, Susan P and Katarina Hamberg (2015). "Women's relative immunity to the socio-economic health gradient: artifact or real?" In: *Global health action* 8.1, p. 27259.
- Plat, Richard (2009). "On stochastic mortality modeling". In: *Insurance: Mathematics and Economics* 45.3, pp. 393–404.
- Pomeroy, Claire (2023). *A Tsunami of Disability Is Coming as a Result of 'Long COVID'*. Accessed: 2024-12-03. URL: <https://www.scientificamerican.com/>

-
- article/a-tsunami-of-disability-is-coming-as-a-result-of-lsquo-long-covid-rsquo/.
- PRA (Apr. 2019). *Enhancing banks' and insurers' approaches to managing the financial risks from climate change (Supervisory Statement SS3/19)*. Accessed: 2025-07-21. URL: <https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/supervisory-statement/2019/ss319.pdf>.
- (Apr. 2025). *Consultation Paper CP10/25: Enhancing banks' and insurers' approaches to managing climate-related risks*. Accessed: 2025-07-21. URL: <https://www.bankofengland.co.uk/prudential-regulation/publication/2025/april/consultation-paper-1025>.
- Public Health, Harvard T.H. Chan School of (2021). *The Next Pandemic: Not If, but When*. Accessed: 2025-02-25. URL: <https://hsph.harvard.edu/news/next-pandemic-not-if-but-when/>.
- Public Health England (2018). *A Review of Recent Trends in Mortality in England*. Public Health England. URL: https://assets.publishing.service.gov.uk/media/5d652e19ed915d53aebba6ea/Recent_trends_in_mortality_in_England.pdf.
- R Development Core Team (2014). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. URL: <https://www.R-project.org>.
- Rabbi, Ahbab Mohammad Fazle and Stefano Mazzucco (2021). “Mortality forecasting with the lee–carter method: Adjusting for smoothing and lifespan disparity”. In: *European Journal of Population* 37, pp. 97–120.
- Rendall, Michael S, Margaret M Weden, Melissa M Favreault, and Hilary Waldron (2011). “The protective effect of marriage for survival: a review and update”. In: *Demography* 48.2, pp. 481–506.
- Ritchie, Hannah and Lucas Rod s-Guirao (2024). “Life expectancy is returning to pre-pandemic levels”. In: *Our World in Data*. URL: <https://ourworldindata>.

-
- org/data-insights/life-expectancy-is-returning-to-pre-pandemic-levels.
- Rocklöv, Joacim and Håkan Sjödin (2020). “High population densities catalyse the spread of COVID-19”. In: *Journal of Travel Medicine* 27.3. DOI: 10.1093/jtm/taaa038. URL: <https://doi.org/10.1093/jtm/taaa038>.
- Ruhm, Christopher J. (2018). *Death and the American Dream: Understanding the Rise of “Deaths of Despair”*. Brookings Institution Press.
- Ruhs, Martin and Emma Quinn (2009). “Ireland: From rapid immigration to recession”. In: *Migration Information Source*, pp. 1–12.
- SAI (Feb. 2019). *Irish Insured Lives Mortality Investigation (IILMI)*. Tech. rep. Accessed: 2025-05-30. Society of Actuaries in Ireland. URL: <https://web.actuaries.ie/sites/default/files/2019-03/190306%20-%20Irish%20Insured%20Lives%20Mortality%20Investigation%20Report%20Final.pdf>.
- SAI (Sept. 2020). *Report on the 2020 Pensioner Mortality Study of Irish Self-Administered Pension Schemes (with addendum dated April 2022)*. Tech. rep. Accessed: 2025-05-30. Society of Actuaries in Ireland. URL: <https://web.actuaries.ie/sites/default/files/story/2022/05/REPORT%20ON%20THE%202020%20PENSIONER%20MORTALITY%20STUDY%20OF%20IRISH%20SELF-ADMINISTERED%20PENSION%20SCHEMES%20%28WITH%20ADDENDUM%20DATED%20APRIL%202022%29.pdf>.
- (2021). *COVID-19 Action Group Blog*. Accessed: September 20, 2024. URL: <https://web.actuaries.ie/press-publications/committee-working-group-outputs/covid-19-action-group/covid-19-action-group-blog>.
- (Apr. 2022). *Mortality Assumptions Review: Retirement Benefit Schemes Transfer Values*. Tech. rep. Society of Actuaries in Ireland. URL: <https://web.actuaries.ie/sites/default/files/story/2022/05/A7%20Mortality%20Assumptions%20for%20Transfer%20Values%20Paper.pdf>.

-
- Sajadi, Mohammad M., Parham Habibzadeh, Anthony Vintzileos, Shervin Shokouhi, Francisco Miralles-Wilhelm, and Anthony Amoroso (2020). “Temperature, Humidity, and Latitude Analysis to Predict Potential Spread and Seasonality for COVID-19”. In: *JAMA Network Open* 3.6. DOI: 10.1001/jamanetworkopen.2020.11834. URL: <https://doi.org/10.1001/jamanetworkopen.2020.11834>.
- Salvagioni, Denise Albieri Jodas, Francine Nesello Melanda, Arthur Eumann Mesas, Alberto Durán González, Flávia Lopes Gabani, and Selma Maffei de Andrade (2017). “Physical, psychological and occupational consequences of job burnout: A systematic review of prospective studies”. In: *PloS one* 12.10, e0185781.
- Samaritans (2019). *Suicide Statistics Report – Latest Statistics for the UK and the Republic of Ireland*. Accessed April 2025. URL: https://media.samaritans.org/documents/SamaritansSuicideStatsReport_2019_Full_report.pdf.
- Sarker, Rapti, ASM Roknuzzaman, Nazmunnaahar, Mohammad Shahriar, Md Jamal Hossain, and Md Rabiul Islam (2023). “The WHO has declared the end of pandemic phase of COVID-19: Way to come back in the normal life”. In: *Health science reports* 6.9, e1544.
- Schaefer, Catherine, Charles P Quesenberry Jr, and Soora Wi (1995). “Mortality following conjugal bereavement and the effects of a shared environment”. In: *American Journal of Epidemiology* 141.12, pp. 1142–1152.
- SEAI (2025). *Fully Funded Energy Upgrades for Eligible Homes*. Accessed: 2025-07-21. URL: <https://www.seai.ie/grants/home-energy-grants/fully-funded-upgrades-for-eligible-homes>.
- Shah, Sunil M, Iain M Carey, Tess Harris, Stephen DeWilde, Christina R Victor, and Derek G Cook (2013). “The effect of unexpected bereavement on mortality in older couples”. In: *American Journal of Public Health* 103.6, pp. 1140–1145.
- Sheehan, Ann and Roger O’Sullivan (2020). *Ageing and Public Health - an overview of key statistics in Ireland and Northern Ireland: Executive Summary*. A report prepared by the Institute of Public Health. Institute of Public Health. URL:

-
- <https://publichealth.ie/sites/default/files/2023-02/wp-content/uploads/2020/04/20200416-AGEING-PUBLIC-HEALTH-SUMMARY.pdf>.
- Shi, Jianjie, Yanlin Shi, Pengjie Wang, and Dan Zhu (2023). “Multi-population mortality modelling: a Bayesian hierarchical approach”. In: *ASTIN Bulletin: The Journal of the IAA* 54.1, pp. 46–74.
- Shor, Eran, David J Roelfs, Misty Curreli, Lynn Clemow, Matthew M Burg, and Joseph E Schwartz (2012). “Widowhood and mortality: a meta-analysis and meta-regression”. In: *Demography* 49, pp. 575–606.
- Shurtleff, Dewey (1955). “Mortality and marital status”. In: *Public Health Reports* 70.3, p. 248.
- Silicon Docklands (2025). *Silicon Docklands*. Accessed: 2025-03-05. URL: <http://www.silicondocklands.com/>.
- Smith, Julia A and Jade A MacLaren (2011). “Some thoughts on the decline of pension schemes”. In: *Management Research Review* 34.12, pp. 1296–1308.
- Statista (2024). *Healthcare expenditure as a share of GDP in Ireland*. Accessed: 2024-12-04. URL: <https://www.statista.com/statistics/429208/healthcare-expenditure-as-a-share-of-gdp-in-ireland/#:~:text=The%20total%20expenditure%20on%20health, before%20declining%20again%20since%202014>.
- Stibich, Mark (2023). *Being Married Improves Life Expectancy*. Accessed: 2024-12-10. URL: <https://www.verywellmind.com/being-married-improves-life-expectancy-2224327#:~:text=Marriage%20was%20one%20of%20the, better%20mental%20and%20emotional%20health..>
- Strausbaugh, Larry J and Carol L Joseph (2000). “The burden of infection in long-term care”. In: *Infection Control & Hospital Epidemiology* 21.10, pp. 674–679.
- Stringhini, Silvia, Cristian Carmeli, Markus Jokela, Mauricio Avendaño, Peter Muenig, Florence Guida, Fulvio Ricceri, Angelo d’Errico, Henrique Barros, Murielle Bochud, et al. (2017). “Socioeconomic status and the 25 × 25 risk factors as de-

-
- terminants of premature mortality: a multicohort study and meta-analysis of 1·7 million men and women”. In: *The Lancet* 389.10075, pp. 1229–1237.
- Stroebe, Margaret, Henk Schut, and Wolfgang Stroebe (2007). “Health outcomes of bereavement”. In: *The lancet* 370.9603, pp. 1960–1973.
- Sullivan, Allison R and Andrew Fenelon (2014). “Patterns of widowhood mortality”. In: *Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 69.1, pp. 53–62.
- Sutcliffe, Charles (2016). *Finance and Occupational Pensions*. Springer.
- Sutherland, Stephani (2023). *Long COVID Now Looks Like a Neurological Disease, Helping Doctors to Focus Treatments*. Accessed: 2024-12-03. URL: <https://www.scientificamerican.com/article/long-covid-now-looks-like-a-neurological-disease-helping-doctors-to-focus-treatments1/>.
- Tang, Kai Hon, Erengul Dodd, and Jonathan J Forster (2022). “Joint modelling of male and female mortality rates using adaptive p-splines”. In: *Annals of Actuarial Science* 16.1, pp. 119–135.
- Taubman, Paul J (1981). *Pensions and Mortality*. Working Paper 811. National Bureau of Economic Research. DOI: 10.3386/w0811. URL: <http://www.nber.org/papers/w0811>.
- Telfar-Barnard, Lucy, Michael G Baker, Nick Wilson, and Philippa Howden-Chapman (2024). “The rise and fall of excess winter mortality in New Zealand from 1876 to 2020”. In: *International journal of biometeorology* 68.1, pp. 89–100.
- The Family Practice (2023). *Divorce Rates in Ireland*. Accessed: 2024-12-10. URL: <https://thefamilypractice.ie/divorce-rates-in-ireland/>.
- The Irish Times (Jan. 2024). *Public sector pension bill surges 17% in three years to €17.57bn*. Accessed: 2025-03-11. URL: <https://www.irishtimes.com/business/work/2024/01/03/public-sector-pension-bill-surges-17-in-three-years-to-1757bn/>.

-
- The King's Fund (2012). *Older People and Emergency Bed Use: Exploring Variation*. Accessed: 2024-12-10. URL: https://assets.kingsfund.org.uk/f/256914/x/ec2d8ad941/older_people_emergency_bed_use_2012.pdf.
- The Pensions Trust (2024). *Collective Defined Contribution (CDC)*. Accessed: 2025-01-07. URL: <https://www.tpt.org.uk/our-pension-services/collective-defined-contribution-cdc/>.
- Thomas, Steve, Conor Keegan, Sarah Barry, Richard Layte, Matt Jowett, Conceição Portela, and Charles Normand (2012). *Resilience of the Irish Health System: Surviving and utilising the economic contraction*. Accessed: 2024-12-05. URL: <https://www.tcd.ie/media/tcd/medicine/pdfs/Resilience-Year-1-Report-2012.pdf>.
- Thompson, William W, David K Shay, Eric Weintraub, Lynnette Brammer, Nancy Cox, Larry J Anderson, and Keiji Fukuda (2003). "Mortality associated with influenza and respiratory syncytial virus in the United States". In: *Jama* 289.2, pp. 179–186.
- Trust for London (2024). *Poverty definitions and thresholds*. Accessed: 2025-05-29. URL: <https://trustforlondon.org.uk/data/poverty-thresholds/>.
- UK Government (2024). *Personal pensions: your rights*. Accessed: 2025-01-07. URL: <https://www.gov.uk/personal-pensions-your-rights>.
- UK Health Security Agency (Aug. 2022). *Seasonal influenza vaccine uptake in children of school age: Winter season 2021 to 2022*. Tech. rep. Accessed: 2025-07-21. UK Health Security Agency. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1096615/annual-childhood-flu-report-2021-2022-updated-aug22.pdf.
- UK NEST Pension (2012). Accessed: 2024-12-03. URL: <https://www.nestpensions.org.uk/schemeweb/nest.html>.
- Van Rijn, Rogier M, Suzan JW Robroek, Sandra Brouwer, and Alex Burdorf (2014). "Influence of poor health on exit from paid employment: a systematic review". In: *Occupational and environmental medicine* 71.4, pp. 295–301.

-
- Villegas, Andrés M, Vladimir K Kaishev, and Pietro Millossovich (2018). “StMoMo: An R package for stochastic mortality modeling”. In: *Journal of Statistical Software* 84, pp. 1–38.
- Walczak, Damian, Jacek Wantoch-Rekowski, and Robert Marczak (2021). “Impact of income on life expectancy: a challenge for the pension policy”. In: *Risks* 9.4, p. 65.
- Walkowiak, Marcin Piotr, Dariusz Walkowiak, and Jarosław Walkowiak (2024). “Exploring the paradoxical nature of cold temperature mortality in Europe”. In: *Scientific Reports* 14.1, p. 3181.
- Wang, Haidong, Katherine R Paulson, Spencer A Pease, Stefanie Watson, Haley Comfort, Peng Zheng, Aleksandr Y Aravkin, Catherine Bisignano, Ryan M Barber, Tahiya Alam, et al. (2022). “Estimating excess mortality due to the COVID-19 pandemic: a systematic analysis of COVID-19-related mortality, 2020–21”. In: *The Lancet* 399.10334, pp. 1513–1536.
- Whelan, S, L Daly, M Hall, R Naqvi, and N Quinn (2024). *Mortality Assumptions for Population and Labour Force Projections 2023-2057*. Accessed: 2025-03-26. URL: <https://www.cso.ie/en/releasesandpublications/ep/p-plfp/populationandlabourforceprojections2023-2057/mortalityassumptions/>.
- Whelan, SF (2009). “Mortality in Ireland at advanced ages, 1950-2006: Part 2: Graduated rates”. In: *Annals of Actuarial Science* 4.1, pp. 67–104.
- Whelan, Shane (2008). “PROJECTING POPULATION MORTALITY FOR IRELAND.” In: *Journal of the Statistical & Social Inquiry Society of Ireland* 37.
- WHO (2020). *Timeline of WHO’s Response to COVID-19*. Accessed: 2025-03-26. URL: <https://www.who.int/news/item/29-06-2020-covidtimeline>.
- WHO (2022). *14.9 Million Excess Deaths Associated with the COVID-19 Pandemic in 2020 and 2021*. Accessed: September 20, 2024. URL: <https://www.who.int/news/item/05-05-2022-14.9-million-excess-deaths-were-associated-with-the-covid-19-pandemic-in-2020-and-2021>.

-
- WHO (2022). *14.9 million excess deaths associated with the COVID-19 pandemic in 2020 and 2021*. News Release. Accessed: 2024-10-09. URL: <https://www.who.int/news/item/05-05-2022-14.9-million-excess-deaths-were-associated-with-the-covid-19-pandemic-in-2020-and-2021>.
- Wikipedia (2025). *Silicon Docks*.
- Williams, Kristi (2004). “The transition to widowhood and the social regulation of health: Consequences for health and health risk behavior”. In: *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 59.6, S343–S349.
- Williamson, Elizabeth J., Alex J. Walker, Krishnan Bhaskaran, and Seb et al. Bacon (2020). “Factors Associated with COVID-19-Related Death Using OpenSAFELY”. In: *Nature* 584, pp. 430–436. DOI: 10.1038/s41586-020-2521-4. URL: <https://doi.org/10.1038/s41586-020-2521-4>.
- Wise, Jacqui (2025). *Life expectancy: England shows biggest slowdown among European countries*.
- Wong, Jackie ST, Jonathan J Forster, and Peter WF Smith (2023). “Bayesian model comparison for mortality forecasting”. In: *Journal of the Royal Statistical Society Series C: Applied Statistics* 72.3, pp. 566–586.
- Wong, Man Kai (2023). “COVID-19 mortality and progress toward vaccinating older adults—World Health Organization, worldwide, 2020–2022”. In: *MMWR. Morbidity and mortality weekly report* 72.
- Wood, Simon N (2001a). “mgcv: GAMs and generalized ridge regression for R”. In: *R news* 1.2, pp. 20–25.
- Wood, Simon N. (2001b). *mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation*. R package version 1.8-41. URL: <https://CRAN.R-project.org/package=mgcv>.
- Wood, Simon N. (2003). “Thin Plate Regression Splines”. In: *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* 65.1, pp. 95–114. DOI: 10.1111/1467-9868.00374.

-
- (2006). *Generalized Additive Models: An Introduction with R*. Chapman & Hall/CRC.
- Wood, Simon N (2017). *Generalized additive models: an introduction with R*. Chapman and Hall/CRC.
- Wood, Simon N. (2020). *mgcv: Generalized Additive Models for R*. Version 1.8-32. Accessed: 2025-04-16. URL: https://cran.r-project.org/src/contrib/Archive/mgcv/mgcv_1.8-32.tar.gz.
- (2025). *mgcv2025*. R package version 1.9-3. URL: <https://rdocumentation.org/packages/mgcv/versions/1.9-3>.
- Woolf, Steven H, Robert E Johnson, Robert L Phillips Jr, and Maike Philipsen (2007). “Giving everyone the health of the educated: an examination of whether social change would save more lives than medical advances”. In: *American journal of public health* 97.4, pp. 679–683.
- Worldometer (2024). *COVID-19 Coronavirus Death Toll*. Accessed: 2025-03-27. URL: <https://www.worldometers.info/coronavirus/coronavirus-death-toll/>.
- Wren, Maev-Ann (2004). “Health spending and the black hole”. In: *Quarterly Economic Commentary*, pp. 1–23.
- Wu, Chenkai, Michelle C Odden, Gwenith G Fisher, and Robert S Stawski (2016). “Association of retirement age with mortality: a population-based longitudinal study among older adults in the USA”. In: *J Epidemiol Community Health* 70.9, pp. 917–923.
- Yang, Lei, Guoyou Qin, Naiqing Zhao, Chunfang Wang, and Guixiang Song (2012). “Using a generalized additive model with autoregressive terms to study the effects of daily temperature on mortality”. In: *BMC medical research methodology* 12, pp. 1–13.
- Zushin, Peter-James H and Joseph C Wu (2025). “Evaluating the benefits of the early use of GLP-1 receptor agonists”. In: *The Lancet* 405.10474, pp. 181–183.