

Contents

Abstract	iii
Zusammenfassung	v
Danksagung	vii
Frequently Used Notation	xiii
List of Acronyms and Abbreviations	xvii
1 Introduction	1
1.1 Outline of this Thesis	4
1.2 Preliminaries	5
2 Stochastic Mortality Models: A Review	7
2.1 Single-Population Mortality Models	7
2.1.1 The Lee-Carter Model	7
2.1.2 The Cairns-Blake-Dowd Model	9
2.1.3 Model Extensions: Cohort Effects and External Information	10
2.1.4 Other Modeling Approaches	12
2.2 Multi-Population Mortality Models	12
2.2.1 The Individual Lee-Carter Model	12
2.2.2 The Augmented Common Factor Model	14
2.2.3 The Common Age Effect Model	15
2.2.4 Applying Clustering Methods	17
2.2.5 Models Based on Reference Populations	18
2.2.6 Other Modeling Approaches	19
2.3 Model Calibration	20
2.3.1 Poisson Maximum Likelihood Estimation	20
2.3.2 The Bayesian Information Criterion	21
2.4 Forecasts and Uncertainty	22
2.4.1 Point Forecasts	22
2.4.2 Prediction Uncertainty	22
2.4.3 Interval Forecasts	24
2.4.4 Evaluating Forecasting Performance	25
2.5 Machine Learning Applications in Mortality Modeling	27

3	Clustering-Based Extensions of the Common Age Effect Model	29
3.1	Algorithms	30
3.1.1	k -means Clustering	30
3.1.2	Augmented Common Factor Clustering	32
3.1.3	Likelihood-Ratio-Based Clustering	35
3.1.4	Fuzzy Maximum Likelihood Clustering	39
3.1.5	Calculating the Number of Free Parameters	51
3.2	Empirical Results	51
3.2.1	Clustering Results	52
3.2.2	Goodness of Fit	58
3.2.3	Forecasting Performance	60
3.3	Conclusion	63
3.A	Results for the Age Group 18 to 52	65
3.B	Robustness Check: Out-of-Sample Results	70
4	Forecasting Mortality with Neural Networks	73
4.1	Neural Network Architectures	75
4.1.1	Feed-Forward Neural Networks	75
4.1.2	Hyperparameter Selection and Model Training	76
4.1.3	Recurrent Neural Networks	79
4.1.4	Convolutional Neural Networks	80
4.2	Prediction Uncertainty	87
4.2.1	Literature Review	88
4.2.2	Our Approach	90
4.3	Empirical Results	91
4.3.1	Goodness of Fit	93
4.3.2	Forecasting Performance	94
4.3.3	Prediction Uncertainty	98
4.3.4	Robustness Check	100
4.3.5	Long-Term Forecasts and Annuity Values	103
4.4	Conclusion	106
4.A	Hyperparameters of the Neural Networks	108
5	COVID-19-Type Mortality Shocks: Impact and Model Adjustments	111
5.1	Data	113
5.2	Measuring the Impact of Mortality Shocks	114
5.2.1	Mortality Statistics	114
5.2.2	Mortality Forecasts and Insurance Contracts	116
5.2.3	Impact of a Mortality Shift on Parameters and Forecasts	118
5.3	Empirical Results: Impact of the COVID-19 Pandemic	122
5.3.1	Mortality Development in 2020	122
5.3.2	Mortality Shock in the Jump-Off Year	127
5.3.3	Mortality Shock before the Jump-Off Year	128
5.3.4	Robustness Check: Using a Different Calibration Method	130
5.3.5	Robustness Check: The Cairns-Blake-Dowd Model	131

5.4	Adjusting Models for Mortality Shocks	131
5.4.1	Forecasting the Period Effect with an ARIMA Model	132
5.4.2	Dealing with Mortality Shocks in an ARIMA Setting	133
5.4.3	A Modified Shock Model Calibration Procedure	137
5.5	Empirical Results: Evaluation of Model Adjustments	137
5.5.1	Checking the Normal Distribution Assumption	137
5.5.2	Evaluating our Shock Model Calibration Procedure	139
5.5.3	Model Parameters	139
5.5.4	Goodness of Fit	141
5.5.5	Backtest	143
5.5.6	Life Insurance and Annuity Values	144
5.5.7	Model Performance under Different Future Scenarios	146
5.6	Conclusion	148
5.A	Recalibration Consistency of the LC Model	150
5.B	Additional Figures for Section 5.3	151
5.C	Defining Scenarios of Future Mortality	156
5.D	Annuity Values	158
6	Outlook	159
	Bibliography	161
	Scientific Career	175
	Wissenschaftlicher Werdegang	177