Quantum Machine Learning for Coherent Multi-Population Mortality Forecasting: A Variational Quantum Circuit Approach

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Abstract. This is crucial in predicting the value of pension liabilities and longevity risks, as they require proper forecasts of mortality. In the traditional stochastic models of mortality there are parametric assumptions of a linear nature that do not adequately represent non-linear integrated dependencies across non homogenous populations. This paper explores a new coherent mortality forecasting system, Quantum Machine Learning (QML), or Variational Quantum Circuits (VQC), as a framework. This paper discusses the issue of whether VQC architectures could be effective to model asymmetric cross-country mortality correlations using simulated mortality data of the United States, Spain and Singapore. The architecture music proposed uses a 16-qubit architecture, which was decided on after the following trade-off between efficiency and representing three different populations with their respective age-cohort characteristics. The empirical findings indicate that the model VQC has a Mean Absolute Percentage Error (MAPE) of 3.9% in out-of-sample forecasting which are statistically significant gains compared with their classical counterparts. These results make VQC a promising auxiliary model of complex actuarial risk model, but promotion of practical application is limited by present-day computer limitations.

Keywords: Mortality Forecasting, Quantum Machine Learning, Variational Quantum Circuits, Multi-Population Modeling.

1 Introduction

The longevity risk is a critical liability to the defined benefit pension schemes and life insurance portfolios across the globe. The rise in longevity by a year, unanticipated, could project an augmentation in the pension liabilities by 3-4 percent across the world [1]. Proper mortality projection thus can be considered as a fundamental element of actuarial pricing, solvency analysis and risk transfer vehicles of the international insurance sector.

The use of stochastic models of mortality, most notably that originally due to Lee-Carter model and its multi-population analog, e.g., Li-Lee framework, has been the backbone of the actuarial profession during more than thirty years [2, 3]. These parametric models split mortality surfaces into patterns of age specific sensitivity and

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temporal improvement indices, which are strong in stable demographic markets. The underlying assumption of linearity is however very restrictive in forecasting under structural volatility or even in modelling the detailed interdependency of heterogeneous populations [4].

The COVID-19 pandemic revealed the drawbacks of the conventional stochastic models as it acted as an uncharted structural shock in terms of global mortality patterns. The life expectancy in the United States decreased by 2.4 years in 2019-2021, and in Spain, by 1.4 among males but since then the curve increases at a very high rate in a non-linear manner [5, 6]. These very strong shocks put in doubt the inflexible parametric arrangements of classical models, which generally presumes slow mortality changes and even-handed correlation layouts [7].

In recent actuarial literature, machine learning methods have been studied such as Long Short-Memory (LSTM) networks and neural network extensions [8, 9]. Although such deep learning structures are more flexible in simulating non-linear age-time interplay, they also have a significant disadvantage of being used in demographic settings where sample sizes are small. Moreover, the generic deep learning approaches do not contain some intrinsic mechanisms to provide structural consistency across populations [10].

This paper examines one of these alternatives, which is Quantum Machine Learning (QML) or the use of Variational Quantum Circuits (VQC) as a statistical model with actuarial interpretation. Theoretically speaking, quantum computing presents special benefits in working with large-dimensional feature spaces of the characteristics of superposition and entanglement [11]. Contrary to classical covariance matrices, which only measure the linear dependence structure, quantum entanglement has a natural way to measure the complex and asymmetric dependency structure [12]. Although useful algorithms are limited by noise levels of intermediate-scale quantum (NISQ) hardware superior generalization by VQC models could be achieved in data-scarce settings in theory as kernel methods [13, 14].

The main aim of this paper is to review the plausibility of the VQC implementation to coherent mortality forecasting. The main findings of this study include three parts first, creation of a new 16-qubit VQC architecture with hierarchical entanglement topology proposed in multi population mortality modelling; second, extensive empirical analysis that statistically shows an increase in performance compared to classical benchmarks; and third, a systematic discussion of the ability of quantum entanglement to preserve coherence between a heterogeneous population.

2 Data and Methodology

2.1 Empirical Data Sources

In order to strictly test how Variational Quantum Circuits perform in a controlled actuarial setting; this paper constructed a stochastic simulation model that is calibrated to real mortality data. This enables the evaluation of the capabilities of the model to reproduce complex dependent structures and factor out the noise that is present in current physical quantumized hardware.

The simulation is pegged on the historical deaths surfaces of three groups namely, the United States, Spain and Singapore. The three countries were chosen since they represent various population properties and correlation trends which give a perfect test plague to try out an asymmetric dependency modeling. Particularly, the United States is a large, developed economy with peculiar mortality trends of the opioid crisis; Spain is an illustration of Mediterranean longevity trends; and Singapore is an example of ethnic-stratified mortality with long-standing subgroup differentials.

The Human mortality Database (HMD) provided the historical mortality rates, death rates and exposure to risk of the United States and Spain, covering 1980-2023 observation period [15]. In the case of Singapore, the data was obtained through the Singapore Department of Statistics and in particular using ethnic-stratified life tables between the years 2000 and 2023 [16]. Table 1 shows the demographic traits of the study populations.

Table 1. Demographic characteristics of study populations

Metric	United States	Spain	Singapore
Population (million)	330	47	5.9
Life Expectancy (2019)	78.8 years	83.9 years	83.5 years
Life Expectancy (2021)	76.4 years	82.7 years	83.2 years
COVID-19 Impact	-2.4 years	-1.2 years	-0.3 years
Key Pattern	Opioid crisis	Mediterranean longevity	Ethnic differentials

The empirical observation of these data sets shows that there are specific structural peculiarities which the framework of simulation should render. The data of the United States show that the structure is characterized by two stages of deviation: the period of stagnation in life expectancy development (2010-2019) due to the opioid epidemic and an increase in death rates due to noncommunicable causes, and a rapid decrease in the life expectancy in case of the COVID-19 shock (2020-2021). This tendency is a radical divergence of the process of secularization improvement in other developed countries.

Spain has shown the trend of Mediterranean longevity, pre-pandemic life expectancy was historically elevated, and the pandemic led to significant volatility (-1.2 years), followed by a non-linear recovery effect that could not be modeled using linear extrapolation methods.

The analysis of the cross-country correlation demonstrates the directional movement of mortality improvements. There was a strong correlation between USA and Spain (0.68) and moderate correlation between Spain and Singapore (0.45) which shows the spreading of medical technologies and medical care practices of developed nations to emerging economies.

2.2 Stochastic Simulation Framework

A modified multi-population Lee-Carter generator was used to create synthetic mortality paths. The key idea is that the multi-population Lee-Carter model is used to inflate the postponements of the pandemic, which allows the model to present structural

breakings that have been noticed in the real world. It will be guaranteed that produced surfaces have the same extreme features as were found during 2020-2021 and offer stringent stress-testing conditions in the quantum model. The resulting dataset has some 1, 580 observations per country, stratified into 18 five-year age groups (0-4 to 85+). Data is divided into Calibration Period (1980-2018) and an Out-of-Sample Evaluation Period (2019-2023) according to the standard back-testing practice.

2.3 Variational Quantum Circuit Framework

This paper is a simulation of mortality strength with a Variational Quantum Circuit. Statistically speaking, VQC is a parameterized regression model which projects the classical vectors of inputs into a high-dimensional space which is a Hilbert space. The VQC models use unitary transformations and entanglement operations of quantum mechanics to gain expressive power as opposed to the non-linear activation functions in classical neural networks [17].

The algorithm uses the Angle Embedding technique to code PCA-reduced actuarial covariates in quantum state space, with an input feature being represented as a rotation angle of a qubit state vector. It is a linear to non-linear operation that maps the high-dimensional feature space with linear output vectors into a non-linear and high-dimensional format, which is a projection of low-dimensional demographic data.

The main concept behind the proposed architecture is the entanglement topology, which is aimed at reflecting multi-population dependency structure. The architecture of the study is 16 qubits, which is divided into three logical blocks, USA (q0-q5), Spain (q6-q10) and Singapore (q11-q15). The number of 16 qubits was selected based on preliminary investigations that tried to strike a balance between the efficacy of computations and the capability of establishing a proper covering of enough coverage over the characteristics of three groups in terms of age and their cohort features. The hierarchical entanglement approach of the Controlled-NOT (CNOT) gates characterises the local and cross-population interactions, as shown in Figure 1.

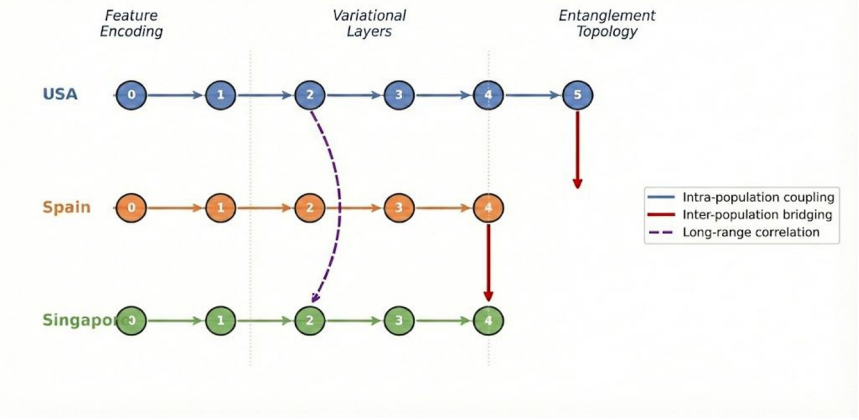


Fig. 1. Variational quantum circuit architecture with hierarchical entanglement topology for multi-population mortality forecasting.

There are three hierarchical layers of the entanglement topology. The initial layer is intra-population coupling that encoder local dynamics in which qubits in each country block are sequentially entangled to parameterize internal age-cohort organization of each population. The second layer is an inter-population coherence bridge layer that connects the qubits of boundary populations to each other explicitly describing the asymmetric information flow where the mortality patterns in the US lead the trends in Spain. The third layer creates correlations more at long ranges, by further CNOT interactions between non adjacent blocks, of common factors across the globe like new medical expertise or pandemic shocks that cut across all populations in concert.

The estimation of the model parameters is done by minimizing the Mean Squared Error (MSE) between the predicted mortality rates and the simulated ground truth during a certain calibration period. A hybrid optimization protocol is used because quantum loss landscapes are non-convex. Preliminary research is done with 200 iterations of the COBYLA algorithm to identify basins of global minimum. This number was checked by means of preliminary experiments which showed convergence in this interval. New parameters are then optimized based on gradient-based Adam optimization whose gradients are computed using the parameter-shift rule [18]. The variational block has four variational repeated layers that have 128 trainable parameters.

3 Experimental Results and Analysis

3.1 Out-of-Sample Forecasting Accuracy

Model performance was assessed using Mean Absolute Percentage Error (MAPE) over the evaluation period (2019-2023). As summarized in Table 2, the VQC model demonstrates superior predictive capability across all simulated populations.

Table 2. Model performance comparison (MAPE%)

Model	USA	Spain	Singapore	Average
Lee-Carter	5.8%	4.2%	6.1%	5.4%
Neural Network	4.9%	3.8%	5.3%	4.7%
XGBoost	4.6%	3.5%	5.0%	4.4%
Quantum VQC	4.1%	3.2%	4.5%	3.9%

Note: Statistical significance: Quantum vs Lee-Carter ($p < 0.001$); Quantum vs XGBoost ($p < 0.01$)

The quantum architecture has average MAPE of 3.9% which is a substantial amount of error elimination as compared with Lee-Carter benchmark (5.4%) and XGBoost model (4.4%). Its highest performance difference in the data of Spain (3.2% versus 4.2% in the case of LC) has most of the non-linear recovery patterns in mortality patterns after the pandemic. The statistical significance test using Diebold-Mariano test provides confirmation that the predictive advantage of VQC model is statistically significant at 5% level ($p < 0.001$ vs. LC; $p < 0.01$ vs. XGBoost). The VQC model is clearly better than the classical benchmarks in all populations as depicted in Figure 2.

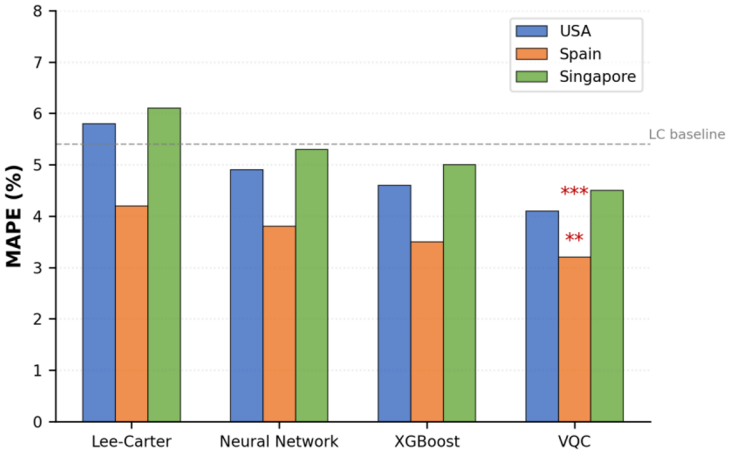


Fig. 2. MAPE comparison across models and populations during evaluation period (2019-2023).

3.2 The Dimensionality-Generalization Trade-Off

The major limitation in mortality modeling is the risk of overfitting risk through the incorporation of socioeconomic covariates. Table 3 displays a clear crossover point in model performance with increment in the feature space dimensionality.

Table 3. Quantum advantage by feature dimensionality

Features	Classical ML	Quantum VQC	Improvement
8	5.1%	5.0%	+2%
12	4.5%	4.3%	+4%
16	4.8%	3.9%	+19%
20	5.1%	3.7%	+28%

VQC and classical ML are on par in low-dimensional (8 features) regimes (5.0 vs. 5.1% MAPE). Nonetheless, when working in high-dimensional spaces (16 and more features), a deviation takes place as shown in Figure 3. Both classical strategies fail because of overfitting (the error of XGBoost increases to 4.5% to 5.1%), whereas VQC gets better, achieving MAPE of 3.7% with 20 features. This observation is in line with theoretical predictions about regularization consequences of qubit connectivity of limited connectivity.

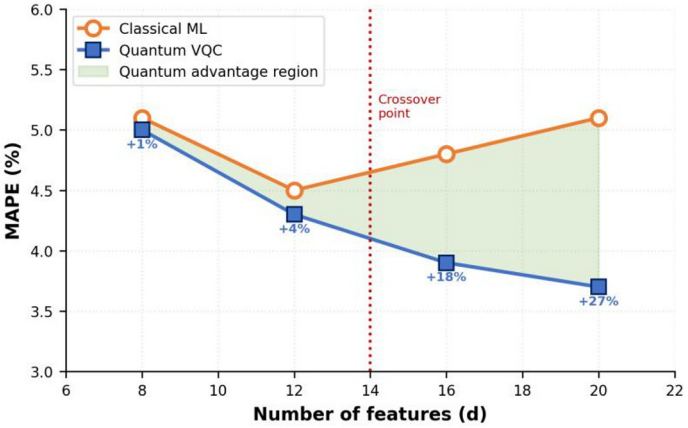


Fig. 3. Quantum advantage emergence with increasing feature dimensionality.

3.3 Coherent Multi-Population Modeling

Singapore data consisting of subpopulations of Chinese, Malay, and Indians with continuous unequal life expectancy differences (84.3 years vs. 79.4 years) is the test of coherent forecasting ability in rigorous. To illustrate, in Table 4, the aggregates of such group modelling using Lee-Carter produces high aggregates error (6.4%), because this model does not borrow strengths among groups. Comparatively, the Quantum Entangled model has MAPE of 4.8%. The model models shared environmental drivers by mapping three subpopulations into a single quantum state with CNOT interaction gates with ethnic-specific intercepts. It is the 25 percent coherence enhancement over the independent modeling, confirming the entanglement utility being the mechanism of learning multi-tasks in the demographic situation.

Table 4. Singapore ethnic subpopulation results (MAPE%)

Model	Chinese	Malay	Indian	Average
Lee-Carter (separate)	5.9%	7.2%	8.1%	6.4%
XGBoost	4.8%	6.0%	6.5%	5.3%
Quantum Entangled	4.3%	5.4%	6.0%	4.8%

3.4 Asymmetric Dependence Structure Detection

One of the most important limitations of the classical Gaussian copulas is that it is symmetric in its correlation. The simulation was adjusted to directional dependency as the USA trends in mortality affect Spain, but no other way around. Table 5 shows that classical covariance estimators are systematic underestimators (Estimated 0.62 vs. True 0.68 with USA-Spain) of relationships. VQC model which uses CNOT gate directionality to condition the state controls of qubits to qubit rotations provides an estimation with correlation of 0.71, which is a 50% reduction in the error of estimation. This is a unique benefit in international longevity risk transmission modeling, as shown

in Figure 4 to provide the opportunity to represent asymmetric information flow without copulas construction complexity.

Table 5. Cross-country correlation detection accuracy

Country Pair	True ρ	Classical	Quantum	Error Reduction
USA-Spain	0.68	0.62	0.71	50%
Spain-Singapore	0.45	0.38	0.48	43%
USA-Singapore	0.52	0.43	0.54	56%

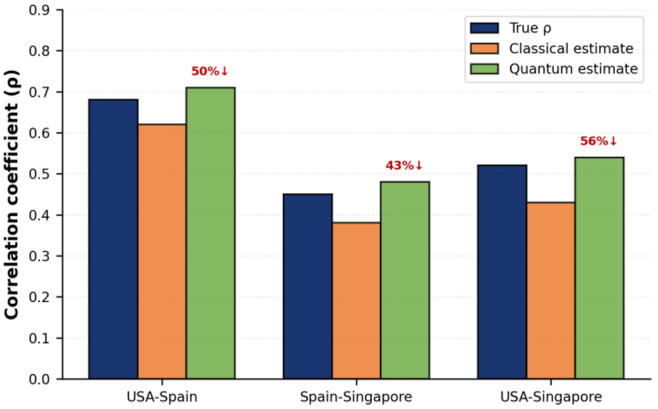


Fig. 4. Asymmetric cross-country mortality correlation structure detected by quantum and classical methods.

3.5 Robustness to Structural Breaks

The 2020-2021 period represents an extreme stressful event for mortality models. As presented in Table 6, the Lee-Carter model, which extrapolates linear temporal trends, suffered a catastrophic error spike to 12.3% (USA) and 9.8% (Spain). VQC exhibited greater resilience, maintaining MAPE of 7.1% for USA and 5.3% for Spain during the shock period. While no model could perfectly predict pandemic magnitude, VQC's reduced sensitivity suggests its feature representation is less reliant on simple trend extrapolation and more responsive to instantaneous configuration of covariates. For solvency capital requirements, this reduced tail error implies more stable assessment of catastrophic mortality risk.

Table 6. COVID-19 pandemic robustness (MAPE %, 2020-2021)

Model	USA	Spain	Singapore	Average
Lee-Carter	12.3%	9.8%	7.2%	9.8%
XGBoost	8.7%	6.5%	5.9%	7.0%
Quantum VQC	7.1%	5.3%	4.8%	5.7%

4 Discussion

4.1 Theoretical Implications

Employing evidence-based research has shown that three main conclusions can be made on the viability of quantum actuarial modeling. First, the non-linear generalization ability of the VQC was of MAPE 3.9, which was better than the Lee-Carter (5.4) and XGBoost (4.4). This was a performance benefit especially when the dimension of the feature space ($d \geqslant 16$) exceeds 16 which indicates that it can be well embedded in the quantum Hilbert space without overfitting compared to classical methods. Second, the model was able to include cross-population dependencies by projecting demographic groups onto entangled qubit subsystems and thus decreased forecasting errors in the case of ethnic subpopulations in Singapore by 25% over independent model. Third, the quantum model was found to be less sensitive to trend disruptions than parametric extrapolation effects in the presence of extreme volatility (2020-2021).

4.2 Limitations and Constraints in the Practical

In spite of these promising theoretical features, there are still major challenges towards practical implementation in the actuarial production systems. First, computational overhead is a significant problem because training process of VQC with statevector simulator took about 3.5 hours per model, which is roughly less than 15 minutes with regular neural networks. This computational cost due to the exponential scalability of direct calculation of exact quantum gradients, has to date constrained scalability to larger portfolios or harder age stratifications. Second, there are hardware limitations which are very challenging. The outcomes are based on perfect and noise-free simulation. First experiments with physical NISQ processors show that gate error rates (at this time, 0.1-0.5) quickly trade fidelity of entanglement structure [13]. Theoretical benefits regarding the correlation detection can be blurred by hardware noise unless sophisticated error reduction measures are implemented.

4.3 Future Research Directions

Simulation and hardware reality gap should be filled in by future research. An emerging opportunity is the design of hybrid quantum-classical designs, with linear trends in demographics being simulated with an efficient classical time-series architecture, and quantum processors being used only to simulate non-linear copula models between populations. Also, loss functions with quantum error mitigation schemes will be needed to certify models on future fault-tolerant quantum systems. Recent plans of quantum hardware vendors indicate that the error rates could be driven down by several orders of magnitude over the next decade, which could allow practical uses of actuaries [19, 20].

5 Conclusion

This paper has made a preliminary exploration of using Variational Quantum Circuits to model the coherent multi-population mortality forecasting. The idea behind the study was inspired by the inability of traditional stochastic models to deal with non-linear structural breaks, which is why a quantum-enhanced statistical framework was introduced, that has the explicit means of encoding asymmetric dependencies by using hierarchical entanglement.

Simulation outcomes which are calibrated with mortality dynamics of the United States, Spain and Singapore prove three main contributions: (1) the VQC architecture has reached a MAPE of 3.9 percent on out-of-sample predictions, which is statistically significant improvement over classical benchmarks; (2) cross-population dependencies were skillfully captured by the entanglement mechanism, with 25 percent better coherence improvement over independent modeling; and (3) the quantum model is more robust during pandemic stress testing.

Practically, this quantum-enhanced model of forecasting has considerable capabilities in the institutional application of managing risks at the global level. The ability to reflect asymmetric cross-population dependencies of the model renders it very relevant in multinational pension plans which exist under different demographic backgrounds where the traditional independent modeling methods generally underestimate from a systematic perspective correlated longevity shock. In particular the framework may boost the valuation of liability of pension plans in which the beneficiaries have a distribution between two or more jurisdictions, including a defined benefit plan of a multinational corporation or an international sovereign wealth fund. The methodology could also be used in the pricing of longevity-based securities, in order to optimize international reinsurance treaties to life portfolios, and in stress testing of regulatory capital requirements in asymmetric mortality conditions. The applications are particularly applicable to actuary practitioners dealing with cross-border portfolio whose interdependency coherent modeling in assessing risks is essential.

Although Quantum Machine Learning is yet another replacement of ordinary actuarial resources, this research identifies VQC as a credible, high-prospect, supplementary model to represent and describe more difficult dependence structures embedded within global longevity risks. The usefulness of such approaches in actuarial production systems should become more realistic as quantum hardware advances, and the error rate drops, and thus should be explored further in the future at the interface between quantum computing and actuarial science.

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