Pension Fund Management with a Machine Learning Strategy

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Recent Development in Pension Industry

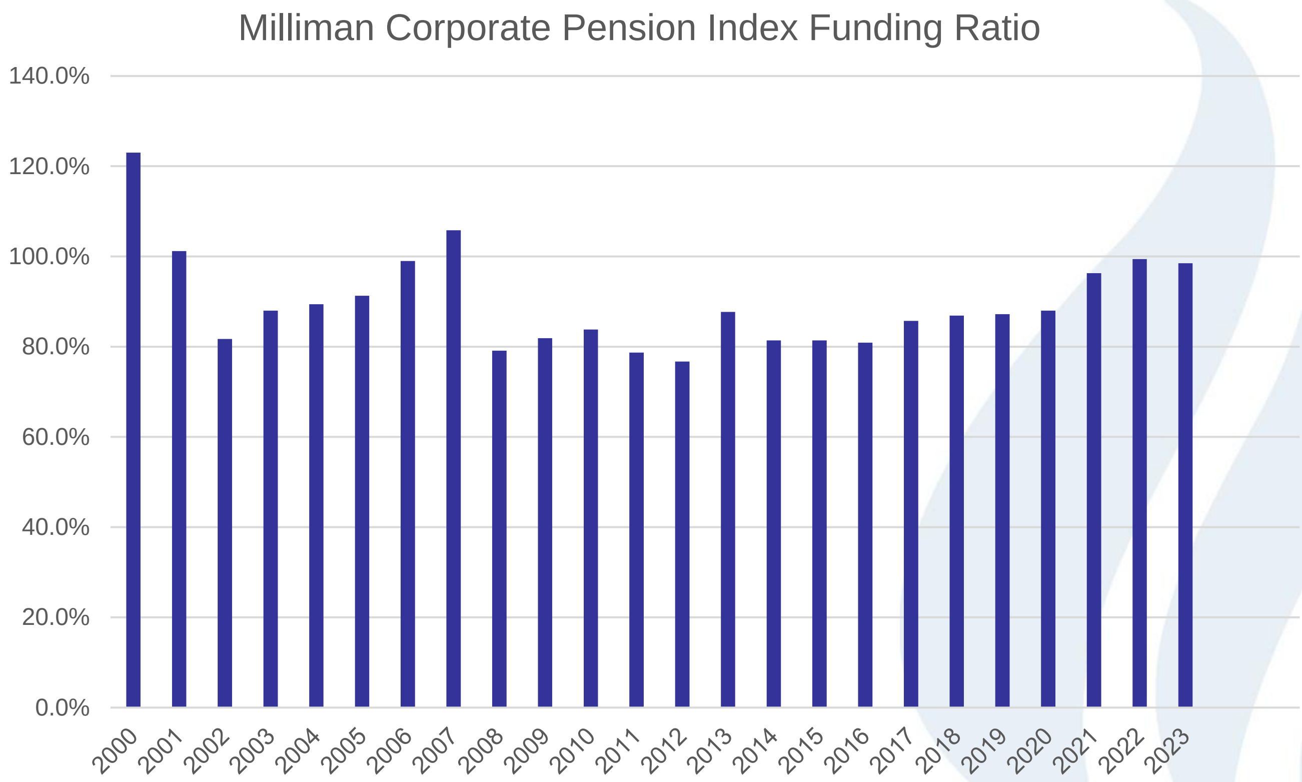
- There has been a surging trend of shifting from DB plans to DC plans in the U.S.
  - Many DB plans are closed to new entrants, and future service accruals are frozen.
  - Pension risk transfers (e.g., buy-in, buy-out) reached record high in 2022/2023 (Buyout assets reached $273.3 billion in Q1 2024).
- Influences of disruptive technologies such as AI
  - Participant engagement
  - Client servicing, plan design and administration
  - Governance
  - Fraud detection
  - Fund management

Challenges in DB Management

- Unique challenges: require consistent fund returns to meet the pension liabilities
  - recent volatile financial markets
  - past long spells of low interest rates
  - prolonged life expectancy of retirees
  - changing pension accounting rule

- Underfunding penalty
  - Amortized deficit contributions
  - More restrictive funding requirements
  - Higher PBGC (Pension Benefit Guaranty Corporation) premiums

Milliman 100 Pension Funding Index



Research Questions

- Objectives:
  - exploit AI/ML methods for pension fund management
  - compare its performance with traditional DB investment framework
- Methodology: a two-stage investment strategy under the liability driven investment (LDI) framework
  - develop an Autoformer-based trading strategy
  - optimal asset allocation using genetic algorithm

Literature Review

- Nonlinearity and Nonstationarity of financial data

- AI/ML for financial time series forecasting:
  - Support Vector Regression, Random Forest, Long Short-Term Memory, Autoregressive/Convolutional/Recurrent Neural Network, and K-Nearest Neighbor (KNN)
  - (see., e.g., Minh et al., 2018; Nikou et al., 2019; Zhong and Enke, 2019; Cervello-Royo and Guijarro, 2020; Lee and Kang, 2020; Nabipour et al., 2020; Shen and Shaq, 2020)

- Gu et al. (2020, RFS): economic gains to investors using ML forecasts can be doubling the performance of leading regression-based strategies.

Literature Review

- Transformer (Vaswani et al., 2017): introduce an attention mechanism to allow for parallelization and improve computational efficiency.

- Various models were proposed: Informer (Zhou et al., 2021), Autoformer (Wu et al., 2021), and Non-stationary (NS) Transformer (Liu et al., 2022).

- Wu (2023) compares SVR, LSTM, Transformer, Informer, Autoformer, and NS Transformer, and finds that Autoformer achieves the highest Sharpe ratio.

Literature Review

- Pension investment:
  - Asset side portfolio optimization: (e.g., Blake et al., 1999; Bikker et al., 2007; Siegmann, 2007; Josa-Fombellida and Rincon-Zapatero, 2010; Iyengar and Ma, 2010; Bikker et al., 2012; Bernard and Kwak, 2016).
  - Surplus management: Sharpe and Tint (1990, JPM); Ezra (1991); Leibowitz et al. (1992);
  - LDI with downside risk management: Ang et al. (2013, JPM); Shang (2021, SOA); Jang et al. (2024)

- Application of AI in pension
  - early retirement, mortality forecasting, pension participation, (e.g., Salazar and Boado-Penas, 2019; Cantor and Shang, 2021; Kemboi Yego et al., 2023)
  - Portfolio optimization: Li and Forsyth (2019), Shang (2021)

Pension Funding Status

- We use the pension funding ratio PF_t to reflect the pension funding status,

$$PF_t = PA_t / PL_t,$$

  - PL_t: pension liability at t based on $N(0)$ employees with jth aged x_j at time 0,

$$PL_t = \sum_{j=1}^{N(0)} PL_{j,t} \cdot 1_{\{T_{x_j} > t\}}, \qquad t = 1, 2, \cdots$$

    where $PL_{j,t}$ is the present value of the pension liability to the jth employee/retiree at time t, and T_{x_j} the future lifetime.

  - PA_t: pension asset

Pension Portfolio Dynamics

- PA_t: the market value of the investment portfolio at time t.

$$PA_t = (PA_{t-1} + NC_t) \sum_{i=1}^{n} w_{i,t} \frac{A_{i,t}}{A_{i,t-1}} - BP_t, \qquad t = 1, 2, \cdots$$

  - $w_{i,t}$: weight of assets invested in index i for period t
  - NC_t: normal cost for period t
  - $A_{i,t}$ the value of the investment on asset i at time t
  - BP_t: pension payments to retirees

- For comparison purposes, we assume there are no other contributions.

Autoformer Architecture

- **Series decomposition block**: seasonal and trend-cyclical parts

$$(Y_{se}, Y_{tr}) = SeriesDecomp(Y) = \left(Y - Y_{tr}, \frac{1}{l} \sum_{i=0}^{l-1} Y_{-i} \right)$$

- **Encoder**: focuses on the seasonal part
  - each layer includes the auto-correlation mechanism and feed-forward neural network
- **Decoder**:
  - utilizes the encoder processed information and predict the seasonal component
  - accumulation structure to form the trend-cyclical part
  - each layer contains two auto-correlation blocks and a feed-forward neural network
- **Auto-correlation mechanism**: capture period-based dependencies via time delay aggregation

Autoformer Architecture

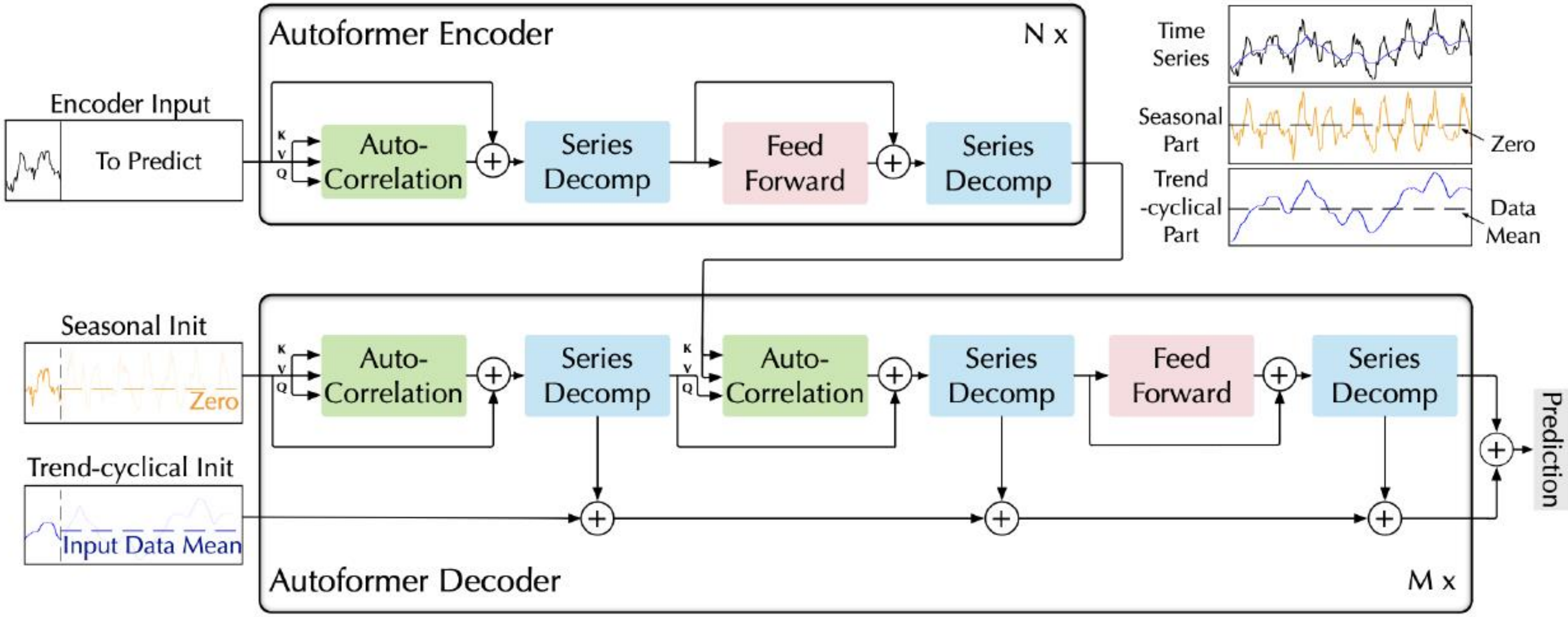


Figure Source: Wu et al. (2021)

Trading Strategy

- Autoformer-based Trading Actions

$$act_{i,t} = \begin{cases} 1, & \hat{r}^p_{i,t} > c_1, \\ 0, & c_2 \le \hat{r}^p_{i,t} \le c_1, \\ -1, & \hat{r}^p_{i,t} < c_2, \end{cases}$$

  - $c_1 > 0$ and $c_2 < 0$: cost thresholds for trade triggering.
- We train the Autoformer model on stocks in S&P 500, and various bond indices based on the quadratic loss errors
- For stocks, we use both return information and technical indicators as input.

- Moving Averages (MA), Relative Strength Index (RSI), Moving Average Convergence/Divergence (MACD) which contains three components (the MACD line, the signal line, and the divergence line), and Bollinger Bands (upper band and lower band).

LDI with Downside Risk

- LDI optimization problem:

$$\max_{\vec{w}_t} E\left[PF_t\right], \qquad \text{subject to} \quad VaR_{1-\epsilon}\left(PF_t\right) \geq l_t$$

- Modified objective function

$$\max_{\vec{w}_t} \left(E\left[PF_t|\mathcal{F}_{t-1}\right] + \alpha\, VaR_{1-\epsilon}\left(PF_t|\mathcal{F}_{t-1}\right)\right)$$

  - $\vec{w}_t$: asset weight vector
  - α: importance level of the VaR measure

- Allocate among asset categories first and then equally divide funds within each asset category
  - Practical challenges of mean-variance framework
  - Equal-weighted portfolios historically outperformed others (Brennan and Wang, 2010; Gu et al., 2020)

Genetic Algorithm

- a heuristic and probabilistic method inspired by the process of natural selection and genetics.
- Main steps
  - **Population initialization**: randomly generate n_{pop} initial chromosomes
  - **Fitness calculation**: calculate the fitness score based on objective function
  - **Parents selection**: select parents with high fitness scores
  - **Crossover**: generate the new offspring chromosomes
  - **Mutation**: randomly modify genes of chromosomes to avoid local optima

Numerical Experiments

- 3-yr final average salary plan of 100 participants with ages 35, 45, ..., 85
  - age and gender weights consistent with the US population
  - same (expected) retirement benefits
  - pension valuation rate: AA bond rate fitted with CKLS interest rate model
  - Lee-Carter model to predict mortality rates
- Pension Assets
  - S&P 500 stocks, 9 investment grade bond indices (corporate AAA, AA, A, BBB, US Treasuries with 3m, 1y, 3-5y, 10y and 30y), cash
  - Data training period: Jan 2000 - Dec 2020
  - Testing period: Jan 2021 - Nov 2023

Model Performance Metrics

- Accuracy: No. of correct / No. of predictions.
- Recall (specificity): No. of corrected positive (negative) predictions / No. of positive (negative) returns.
- PPV (NPV): No. of corrected positive (negative) predictions/ No. of positive (negative) predictions.

	bonds	stocks
Accuracy	0.64	0.55
Recall	0.88	0.90
Specificity	0.41	0.17
Positive Predictive Value	0.58	0.55
Negative Predictive Value	0.78	0.59

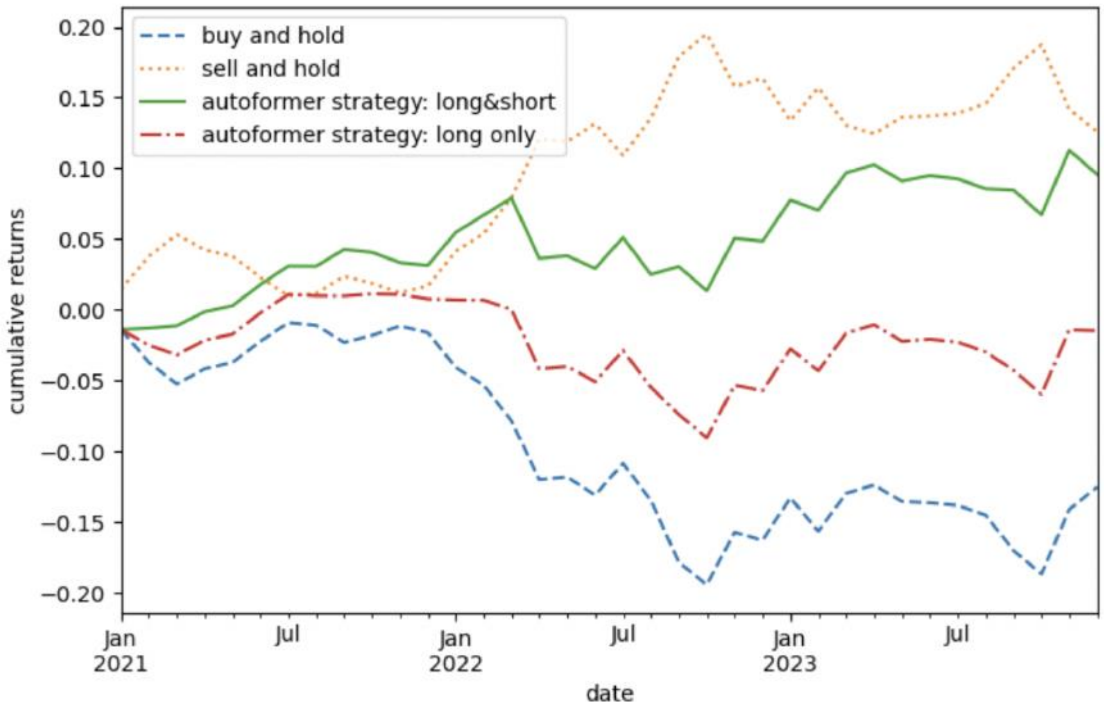
Sharpe Ratio and Maximum Drawdown

	bonds			
	baseline		strategy	
	buy and hold	sell and hold	long&short	long only
Sharpe ratio	-0.58	0.58	**0.62**	-0.005
Annualized return	-0.043	0.042	0.037	-0.002
Annualized volatility	0.072	0.072	0.061	0.061
Maximum drawdown	-0.18	-0.07	-0.065	-0.098

	stocks			
	baseline		strategy	
	buy and hold	sell and hold	long&short	long only
Sharpe ratio	0.6	-0.6	**1.05**	0.84
Annualized return	0.098	-0.11	0.158	0.128
Annualized volatility	0.18	0.18	0.151	0.16
Maximum drawdown	-0.2	-0.32	-0.14	-0.16

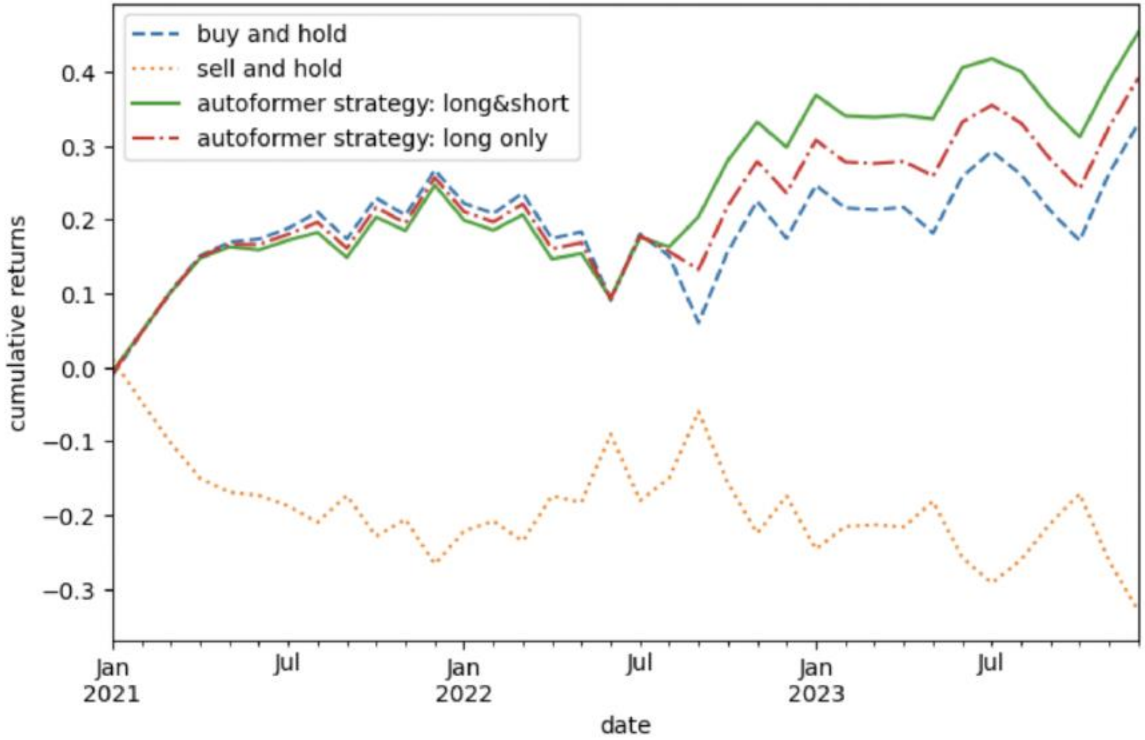
Bond Average Cumulative Return

Figure 1: Cumulative Returns of Different Strategies on the Bond Portfolio



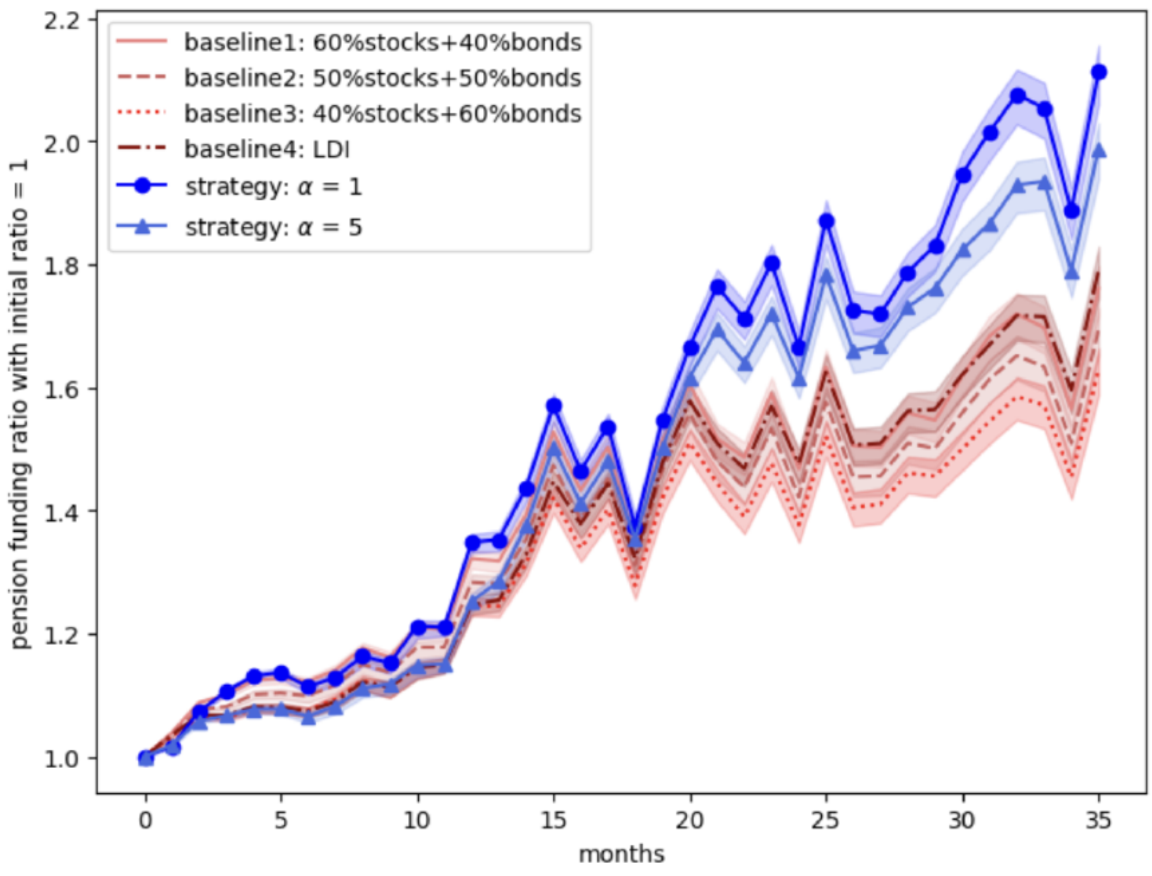
Stock Average Cumulative Return

Figure 2: Cumulative Returns of Different Strategies on S&P 500



Pension Funding Ratio (L&S, 100% Initial FR)

Figure 3: Evolvement of Pension Funding Ratio under Different Investment Strategies with 100% Initial Funding Ratio



Returns and Cumulative PFR

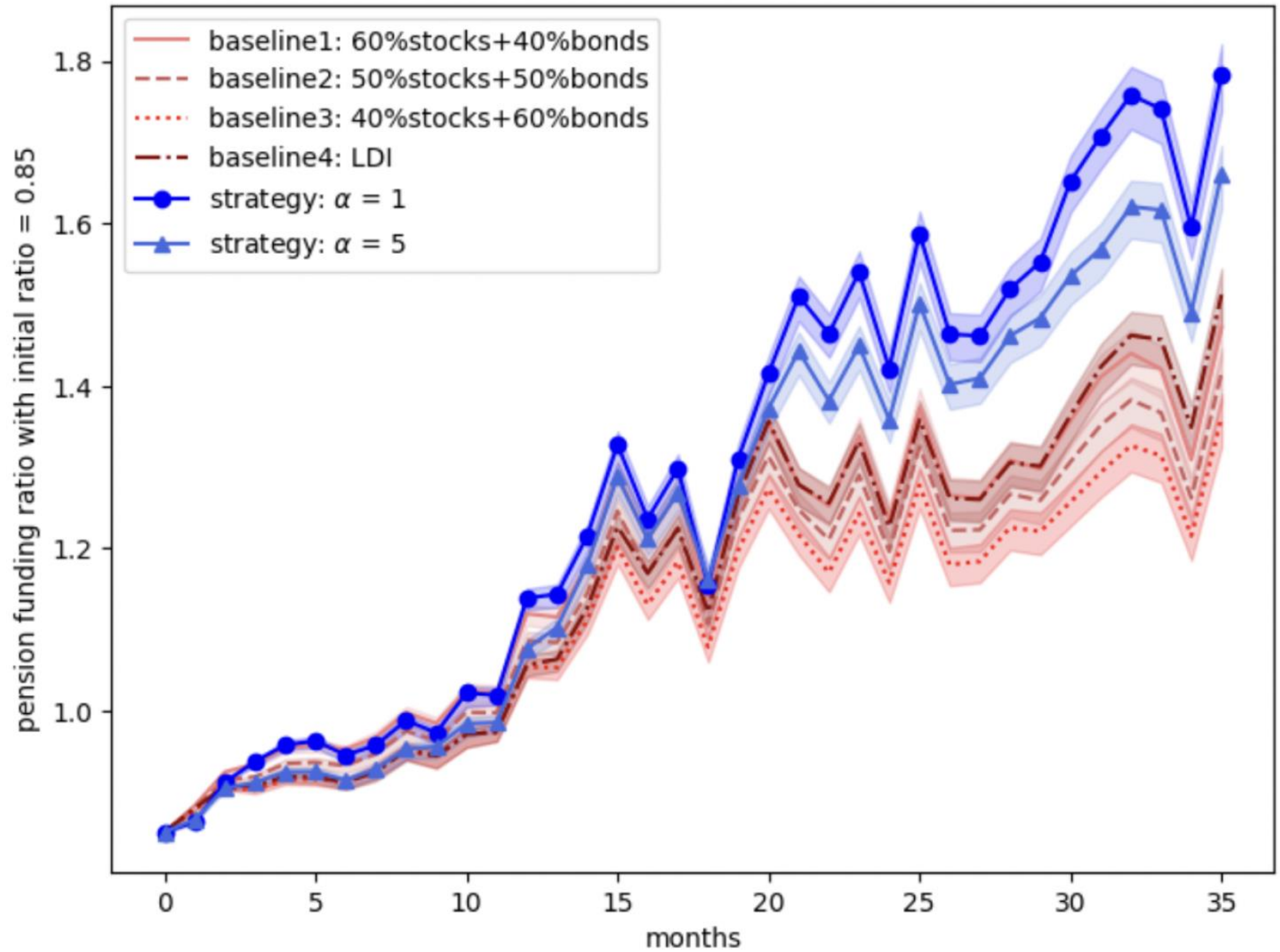
	annualized returns	cumulative returns	cumulative PFR
baseline1	0.021	0.063	1.76
baseline2	0.009	0.026	1.69
baseline3	-0.004	-0.011	1.62
baseline4	0.027	0.083	1.79
strategy: $\alpha = 1$	0.084	0.266	2.11
strategy: $\alpha = 5$	0.063	0.196	1.99

Average Weights of Assets

	Stock Long	Stock Short	Bond Long	Bond Short	Cash
Baseline 1	40%	0	60%	0	0
Baseline 2	50%	0	50%	0	0
Baseline 3	60%	0	40%	0	0
Baseline 4	40%	0	42%	0	18%
Strategy: α=1	69%	11%	11%	3%	6%
Strategy: α=5	39%	6%	34%	13%	9%

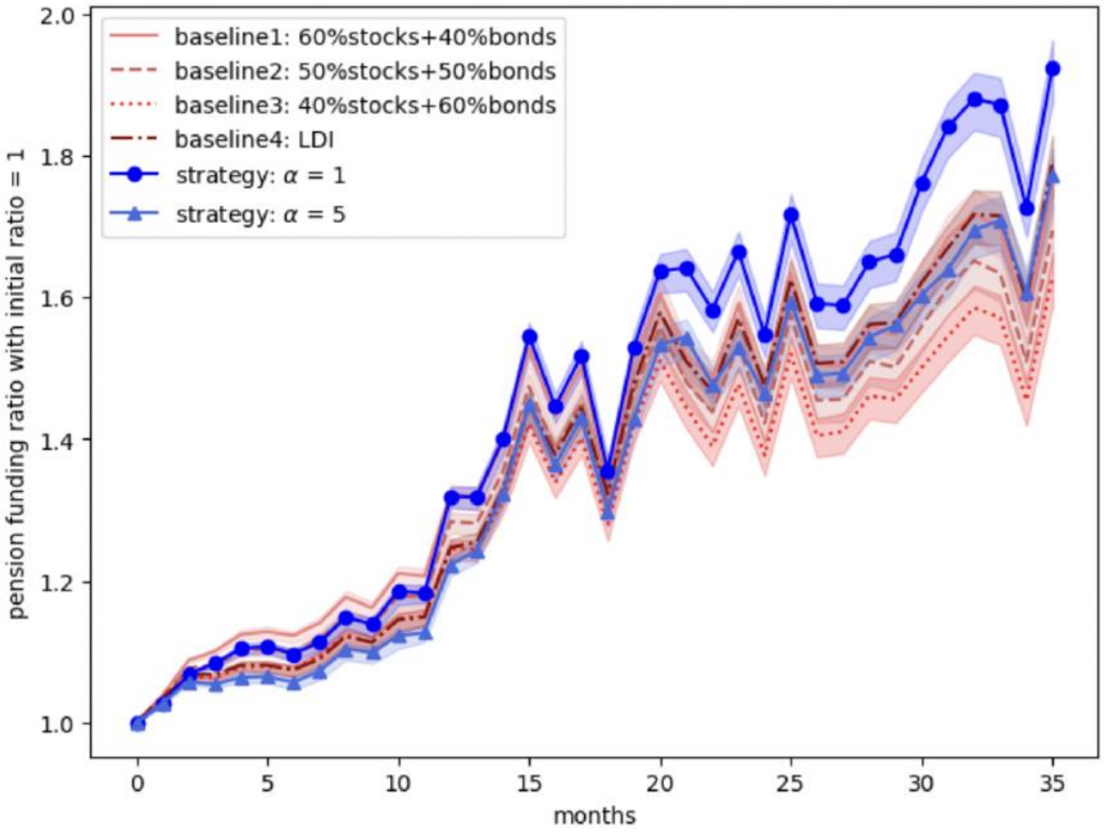
Pension Funding Ratio (L&S, 85% Initial FR)

FIGURE 7. Evolvement of Pension Funding Ratio under Different Investment Strategies with 85% Initial Funding Ratio



Pension Funding Ratio (Long, 100% Initial FR)

Figure 4: Evolvement of Pension Funding Ratio under Autoformer-Based Long-Only Investment Strategies with 100% Initial Funding Ratio



Conclusions

- We introduced an Autoformer-based investment strategy for pension fund management.
- Strategy-based returns and volatilities are used for portfolio optimization under LDI framework.
- Equal-weighted allocations within each asset category may provide more stable returns by avoiding risk concentration.
- ML investment methods would significantly improve pension fund performance.

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Questions? Comments?

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