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Neural Networks for Quantitative Resilience Prediction

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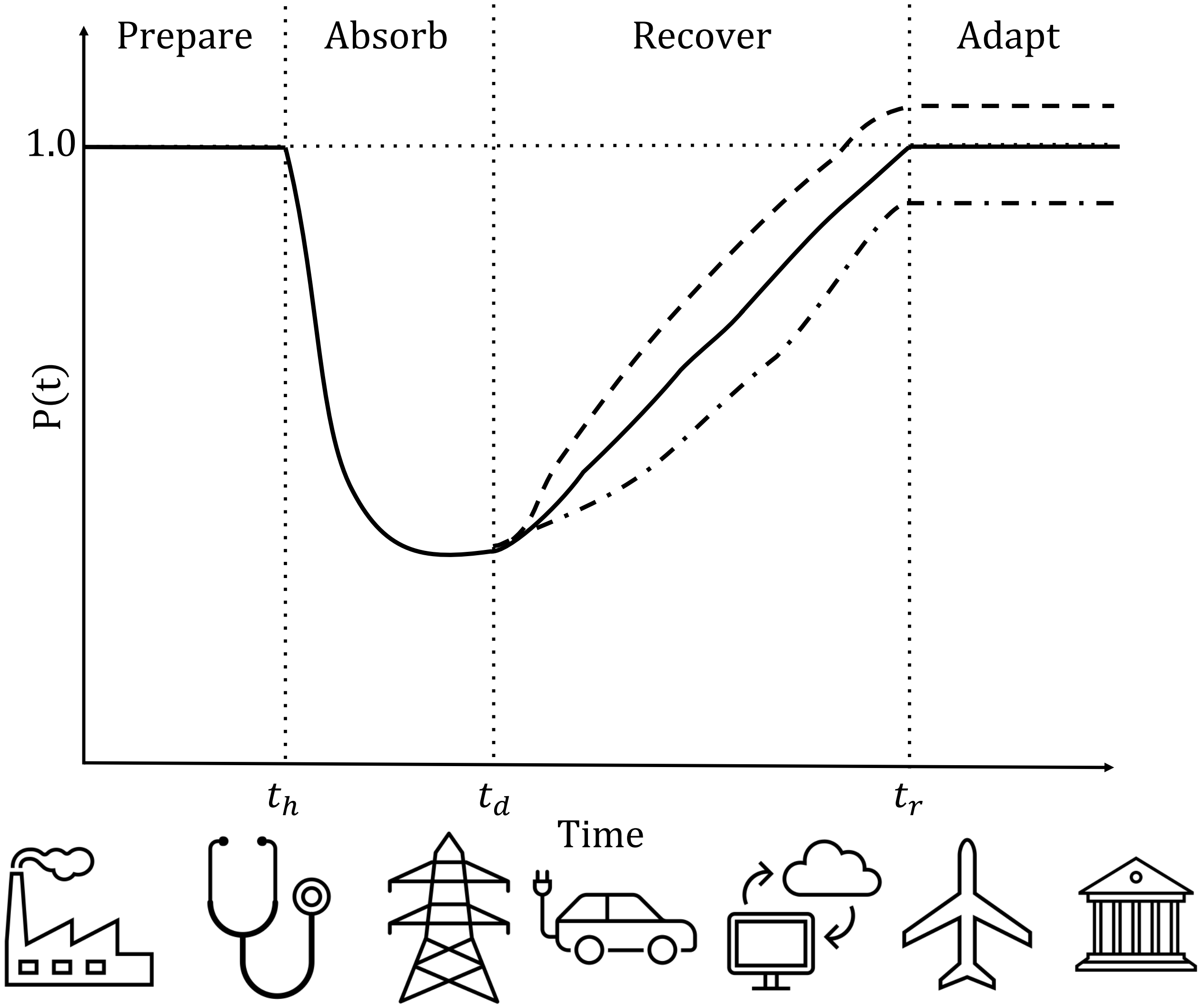
Introduction

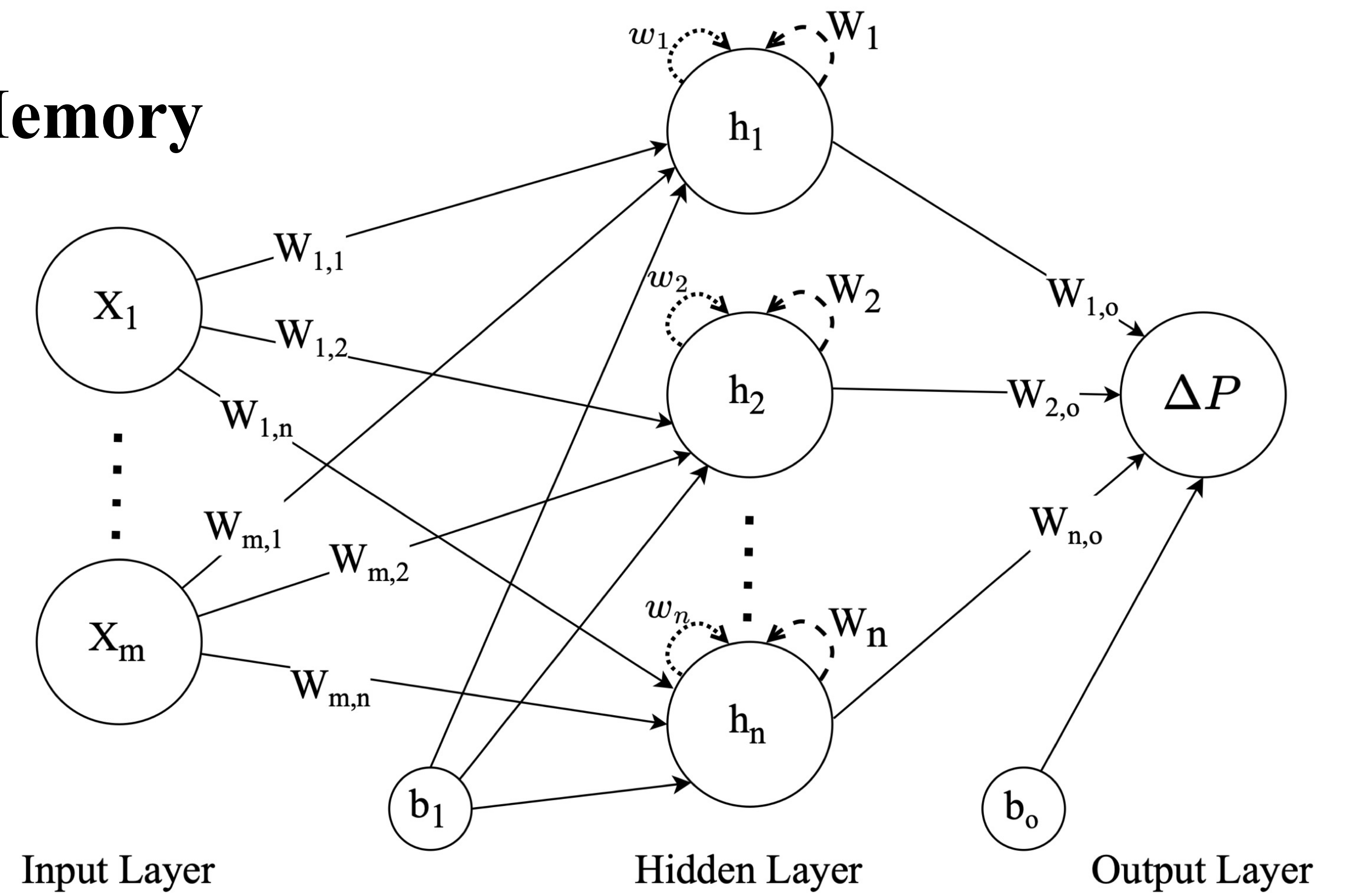
- **Relevant past studies**
  - Resilience metrics, Markov processes, Bayesian Networks and Petri nets;
  - Multiple Linear Regression with Interaction (MLRI).
  - Mostly, to improve future design or limited to smooth trends.
- **Predictive Resilience Modeling**
  - Track and predict system resilience including negative and positive factor driving deterioration and recovery in the system performance.
  - A discrete resilience curve incorporating covariates can be described as:

$$P(i) = P(i-1) + \Delta P(i)$$



Contributions:

Long Short-Term Memory



Model Assessment

- **Predictive Mean Squared Error (PMSE):** computes the mean discrepancy of the model estimates from the actual data considering the test data.
  - **Validation Mean Squared Error (VMSE):** Considers the validation data.
  - **Mean Squared Error (MSE):** Considers the entire data.
- **Mean Absolute Percentage Error (MAPE):** quantifies the mean accuracy of time-dependent problems.
- **Adjusted Coefficient of Determination (r^2_{adj}):** measures the variation in the dependent variable that is explained by the independent variables incorporated into the model.

Feature Selection

There are two steps to select the most relevant subset of covariates:

1. Perform a forward selection search to rank subsets of k covariates according to a heuristic "merit" function:

$$M_s = \frac{k\,\overline{r_{co}}}{\sqrt{k + k(k-1)\overline{r_{cc}}}}$$

2. Create and train models with the highest-ranked subsets of covariates in the previous step. Then, evaluate models and select the one that achieves the highest r^2_{adj} and smallest overall error.

Illustrations:

Table 1: Covariates collected from January 2020 to November 2022.

	Covariate Name		Covariate Name
X_1	Number of Deaths	X_{11}	Treasury Yield Curve
X_2	Number of Cases	X_{12}	Standard & Poor's 500 Index Stock Market
X_3	Stringency Index	X_{13}	Durable Goods Orders
$\boldsymbol{X_4}$	**Workplace closures (policies)**	$\boldsymbol{X_{14}}$	**New Orders Index**
X_5	Number of visitors to workplace (%)	X_{15}	Consumer Confidence Index
X_6	Consumer Activity (%)	X_{16}	Federal Funds Rate
$\boldsymbol{X_7}$	**Unemployment Benefits (million)**	X_{17}	Mortgage Rate
X_8	Overall population fully vaccinated (%)	X_{18}	Personal Consumption Expenditures
X_9	Number of cases in vaccinated people	$\boldsymbol{X_{19}}$	**Industrial Production**
X_{10}	Face covering (policies)	P	COVID-19 US nonfarm jobs

Illustrations:

Table 2: Results of 1^{st} step of feature selection:

Feature Subset	**k**	M_s
X_{19}	1	0.5567882
X_{19}, X_{14}	2	0.6151150
X_{19}, X_{14}, X_4	3	0.6257571
X_{19}, X_{14}, X_4, X_7	4	0.6208308

Table 3: NN hyperparameters:

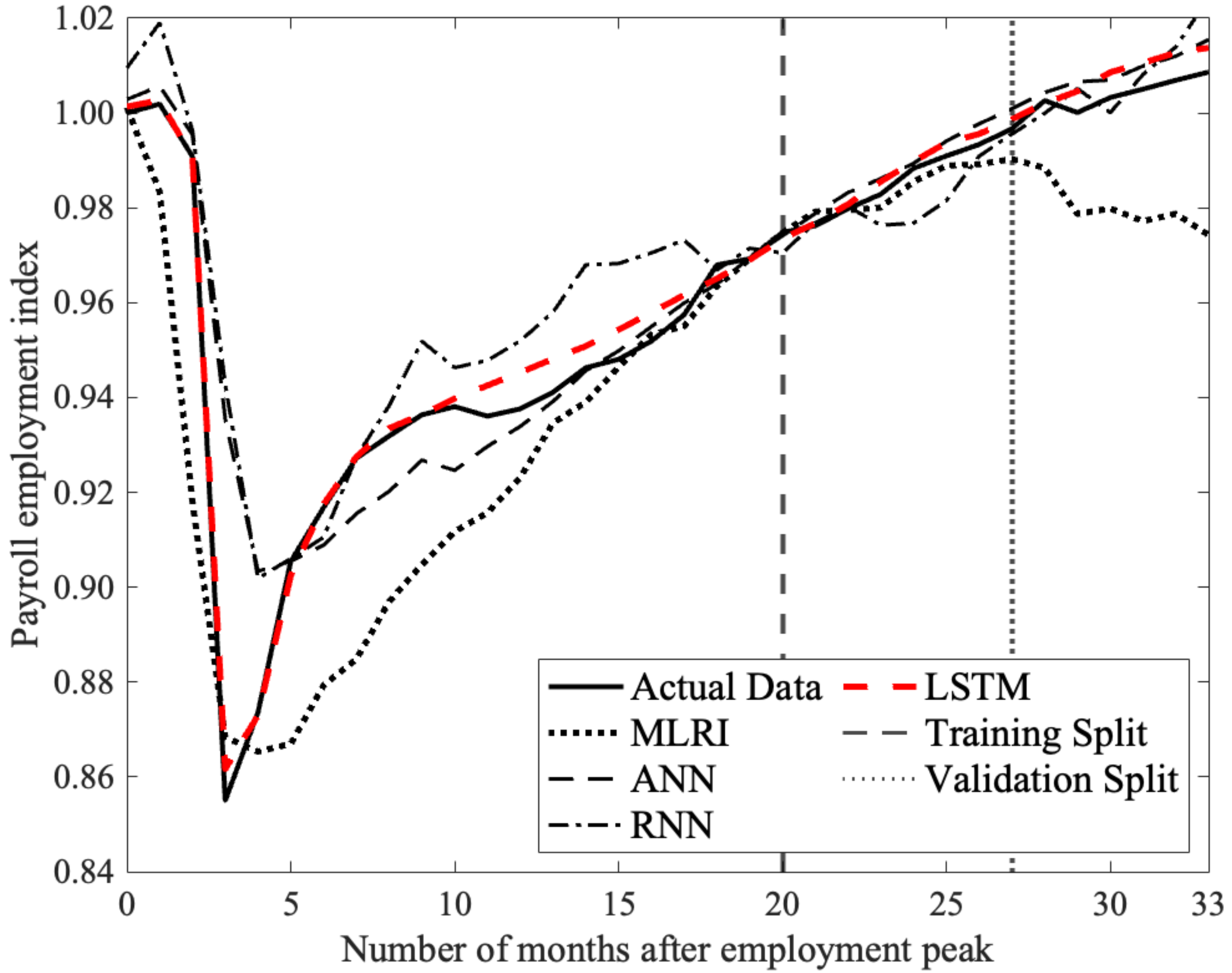
Optimizer	Adam
Learning Rate	0.01
Neurons in the hidden layer	1 -- 15
Max. number of Epochs	1000
Earlier Stopping Condition	Yes

Table 4: Results of 2^{nd} step of feature selection:

Model	**Training Split**	**MLRI**	**ANN**	**RNN**	**LSTM**
Covariates Subset		X_{19}, X_{14}	X_{19}, X_{14}, X_4	X_{19}, X_{14}, X_4, X_7	X_{19}, X_{14}, X_4, X_7
Neurons		-	3	12	7
PMSE	60	0.0002884	0.0000247	0.0000498	**0.0000205**
	70	0.0004306	0.0000731	0.0001766	**0.0000006**
VMSE	60	-	0.0000085	0.0000415	**0.0000035**
	70	-	0.0000094	0.0000182	**0.0000031**
MSE	60	0.000538	0.000245	0.000355	**0.000015**
	70	0.000553	0.000272	0.000320	**0.000017**
MAPE	60	1.70	0.81	1.21	**0.32**
	70	1.73	0.81	1.05	**0.29**
r^2_{adj}	60	0.6087	0.8154	0.7241	**0.9885**
	70	0.5978	0.7952	0.7512	**0.9867**
Average Epochs	60	-	546	**406**	641
	70	-	609	**457**	598

Illustrations:

Figure 1: Model fit of best models using 60% of the data for training.



Conclusion

- **Summary**
  - Presented three alternative neural network models, including ANN, RNN and LSTM, to model and predict system resilience considering disruptive events and restorative activities that characterize the degradation and recovery in the system performance.
- **Results**
  - Neural network approaches can accurately and efficiently track and predict system resilience finding application in many domains;
  - All proposed approaches outperformed the MLRI model;
  - LSTMs exhibited an improvement of over 60% in the r_{adj}^2 and a 34.07-fold reduction in the predictive error (PMSE).
- **Future Research**
  - Explore more challenging data sets including multiple shocks and different applications.
  - Apply alternative neural network model such as Gated Recurrent Units.

Thank you!