

# University of West Florida

Capston Project In Data Science IDC-6940 | Professor Dr. Shusen Pu

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## **Intelligent Inventory Optimization with Deep Learning and Reinforcement Learning.**

### **Introduction**

#### **Problem Definition**

In today's dynamic global economy, accurate inventory forecasting remains one of the most complex and impactful challenges in supply chain management. Variability in consumer demand, fluctuating supplier lead times, and unpredictable disruptions can lead to costly stockouts or excess inventory. These inefficiencies directly affect operational costs, profit margins, and sustainability outcomes. The research problem addressed in this project is how to design intelligent forecasting and inventory optimization systems that accurately predict product demand and dynamically adjust reorder policies under uncertainty. From a data science perspective, this problem requires the integration of statistical modeling, time series forecasting, and machine learning-based decision-making under stochastic conditions.

#### **Context and Background**

Traditional forecasting methods, such as Exponential Smoothing and ARIMA models, have long been used to predict demand trends. However, their linear assumptions and limited adaptability often fail to capture nonlinear and temporal dependencies inherent in large-scale inventory systems. Recent advances in Deep Learning (DL) and Reinforcement Learning (RL) have introduced data-driven methods capable of learning complex temporal relationships and adaptive decision-making strategies.

For instance, Long Short-Term Memory (LSTM) networks have shown superior performance in capturing long-term dependencies in time series data, while Convolutional Neural Networks (CNNs) can extract spatial and sequential features useful for multivariate forecasting. In contrast, Reinforcement Learning — particularly Deep Q-Networks (DQN) and Proximal Policy Optimization (PPO) — enables systems to optimize inventory policies by continuously interacting with an environment and receiving feedback in the form of rewards or penalties.

This project builds upon recent research demonstrating the convergence of these fields. Pasupuleti et al. (2024) highlight that combining ML and RL methods improves supply chain agility and reduces waste through adaptive decision-making. Similarly, Sathish et al. (2024) show that Gradient Boosting and other machine learning algorithms outperform traditional forecasting models. Collectively, these studies establish a theoretical foundation for using hybrid models to enhance accuracy and efficiency in inventory management.

## **Objectives and Goals**

The objectives of this research are threefold:

**Forecasting Accuracy:** Develop and evaluate deep learning models (e.g., LSTM, CNN-LSTM) to predict product-level demand across multiple time horizons.

**Dynamic Inventory Optimization:** Implement a reinforcement learning framework that learns optimal reorder policies through continuous interaction with simulated inventory environments.

**Comparative Evaluation:** Benchmark the performance of deep learning and RL-based methods against classical statistical models (ARIMA, Exponential Smoothing) using quantitative performance metrics such as MAE, RMSE, and cost efficiency.

The overarching goal is to create an intelligent inventory optimization system capable of adapting to changing demand patterns and improving decision-making accuracy at scale.

## **Summary of Approach**

The study integrates Deep Learning and Reinforcement Learning methodologies using the Global Product Inventory Dataset 2025 from Kaggle. The dataset contains global-level records of product demand, inventory quantities, supplier information, and lead times. First, exploratory data analysis (EDA) and feature engineering will prepare time-dependent variables. Next, deep learning models will forecast demand, while reinforcement learning agents will optimize restocking actions within a simulated environment. Model performance will be evaluated using both statistical accuracy measures and business-oriented metrics such as cost savings and service levels.

## **Methods**

### **Data Acquisition and Sources**

The dataset used in this project is the Global Product Inventory Dataset 2025 (Keyushnisar, 2025) available on Kaggle. It contains over 100,000 observations of product-level inventory and demand records across multiple global warehouses and suppliers. Key features include product

identifiers, stock levels, sales quantities, reorder amounts, lead times, and timestamps, enabling time-series analysis.

Prior to modeling, data preprocessing steps will include:

- Data Cleaning: Handling missing values and outliers through imputation and winsorization.
- Feature Engineering: Creating time-based variables such as rolling averages, lag features, and reorder point estimates.
- Normalization: Applying Min-Max scaling and one-hot encoding for categorical variables to optimize model training performance.

Data Source: <https://www.kaggle.com/datasets/keyushnisar/global-product-inventory-dataset-2025>

## Mathematical and Statistical Models

### 1. Time Series Forecasting Models

The deep learning component employs LSTM and CNN-LSTM architectures to model temporal dependencies and nonlinear demand relationships.

Loss Functions: Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE).

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i|$$
$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}$$

Baseline comparisons will include ARIMA, Exponential Smoothing, and XGBoost models to establish a statistical benchmark.

### 2. Reinforcement Learning Model

The decision-making component uses a Deep Q-Network (DQN) to simulate inventory control under uncertainty.

State Space (S): Current stock level, predicted demand, lead time, holding cost, shortage cost.

Action Space (A): Discrete reorder quantities.

Reward Function (R):

$$R_t = -(C_h \times H_t + C_s \times S_t)$$

where  $C_h$  and  $C_s$  represent holding and shortage costs, respectively, and  $H_t$   $S_t$  are the respective quantities at time  $t$ .

The DQN is trained using experience replay and an  $\epsilon$ -greedy exploration policy to balance exploitation and exploration.

## Experimental Design and Analytical Procedures

The analysis proceeds through the following steps:

1. Exploratory Data Analysis (EDA): Examine distributions, seasonality, and correlation among features.
2. Feature Engineering: Construct lagged and rolling features to enhance temporal signal representation.
3. Model Training and Validation:
  1. Split dataset into training (70%), validation (15%), and testing (15%) sets.
  2. Train and tune models using grid search and cross-validation.
4. Performance Evaluation:
  1. Forecasting models: MAE, RMSE, and MAPE.
  2. Reinforcement learning agent: total cost reduction, service level (fill rate), and stockout frequency.
5. Comparison and Integration: Combine best-performing models into a unified hybrid system for evaluation.

## Software and Tools

The project is implemented primarily in Python and R, using the following tools:

- Python libraries: TensorFlow, Keras, Scikit-learn, XGBoost, Stable Baselines3
- Data analysis and visualization: pandas, NumPy, matplotlib, seaborn
- R environment: Bibliometrix for analytical reference management
- Development environment: Jupyter Notebook and Google Colab

## **Ethical Considerations**

Although the dataset is publicly available and anonymized, ethical standards for data use and reproducibility are upheld. The project ensures:

- Transparency in data preprocessing and modeling decisions.
- Reproducibility of results through documented code and parameter logs.
- Proper citation of all data and research sources.

## **First Step to Begin the Project**

The first step to begin this project is to set up the computational environment and prepare the dataset for analysis. This includes:

1. Creating a project repository in GitHub or local workspace for version control and reproducibility.
2. Installing essential software and libraries, including Python (TensorFlow, Keras, pandas, NumPy, Matplotlib, Scikit-learn, XGBoost) and Jupyter Notebook or Google Colab for experimentation.
3. Downloading the Global Product Inventory Dataset 2025 from Kaggle and exploring its structure to understand key attributes such as product category, stock quantity, sales volume, and time periods.
4. Conducting an initial exploratory data analysis (EDA) to identify missing values, inconsistencies, and key patterns.
5. Documenting preprocessing steps to ensure data integrity before modeling.
6. This setup phase forms the foundation for all subsequent modeling, ensuring the research environment is stable, reproducible, and aligned with data science best practices.

## References

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