

# Deep Learning for Time Series Forecasting: A Survey

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## Abstract

Time series forecasting (TSF) has long been a crucial task in both industry and daily life. Most classical statistical models may have certain limitations when applied to practical scenarios in fields such as energy, healthcare, traffic, meteorology, and economics, especially when high accuracy is required. With the continuous development of deep learning, numerous new models have emerged in the field of time series forecasting in recent years. However, existing surveys have not provided a unified summary of the wide range of model architectures in this field, nor have they given detailed summaries of works in feature extraction and datasets. To address this gap, in this review, we comprehensively study the previous works and summarize the general paradigms of Deep Time Series Forecasting (DTSF) in terms of model architectures. Besides, we take an innovative approach by focusing on the composition of time series and systematically explain important feature extraction methods. Additionally, we provide an overall compilation of datasets from various domains in existing works. Finally, we systematically emphasize the significant challenges faced and future research directions in this field.

时间序列预测（TSF）长期以来是工业界与日常生活中的关键任务。传统统计模型在能源、医疗、交通、气象和经济等领域的实际应用场景中，特别是对预测精度要求较高时，往往存在一定局限性。随着深度学习的持续发展，近年来时间序列预测领域涌现出大量新型模型。然而现有综述研究尚未对该领域广泛采用的模型架构进行统一归纳，亦未对特征提取方法与数据集相关研究作出系统梳理。为填补这一空白，本综述通过全面研究已有成果，从模型架构角度总结了深度时间序列预测（DTSF）的通用范式；创新性地聚焦时间序列的构成要素，系统阐释了重要特征提取方法；同时对现有研究中涉及的多领域数据集进行了整体汇编。最后，我们系统性地强调了该领域面临的重大挑战与未来研究方向。

时间序列广泛存在于人类生产生活的各个领域，是记录历史事件的重要维度。预测作为其核心任务，旨在利用序列中的历史信息推演未来趋势（Hyndman与Athanasopoulos, 2018; Petropoulos等, 2022）。该技术在诸多与人类生活密切相关的领域具有重要应用价值，包括能源生产与消费（Deb等, 2017; Li等, 2019b; Saxena等, 2019; Rajagukguk等, 2020; Zhao等, 2016; Toubeau等, 2018）、气象变化（Mudelsee, 2019; Zaini等, 2022）、金融证券与计量经济学（Sezer等, 2020; Chen与Chen, 2015; Callot等, 2017; Andersen等, 2005; Luo等, 2018; Kalra等, 2024; Singh等, 2023）、销售与需求预测（Böse等, 2017; Bandara等, 2019）、城市交通流量（Tedjopurnomo等, 2020; Lv等, 2014; Li等, 2017）以及健康医疗等民生领域（Piccialli等, 2021; Kaushik等, 2020; Topol, 2019; Mishra等, 2024）。

机器学习、数据科学以及运用运筹学与统计方法的研究团队已对时间序列预测领域进行了广泛探索（Fuller, 2009; Faloutsos等, 2018, 2019b,a）。统计模型通常通过考量非平稳性、线性关系及特定概率分布，依据历史数据的均值、方差和自相关等统计特性来推断未来趋势。而机器学习模型则直接从数据中学习规律与规则。随着深度学习技术的兴起（Rosenblatt, 1957）与快速发展（Goodfellow等, 2016; LeCun等, 2015），越来越多的神经网络模型被应用于时间序列预测。相较于前两种依赖领域专业知识或显式特征工程的方法，深度学习能够自主从复杂数据中提取精细的时间特征与模式。这种特性使其能够捕捉长期依赖关系和复杂关联，最终提升预测精度。本文中，我们将时间序列预测深度学习相关研究简称为DTSF研究，时间序列预测则缩写为TSF。

**Keywords:** Time Series Forecasting, Model Architecture Paradigm, Feature Extraction Methodology, Multivariate Time Series Data  
关键词：时间序列预测、模型架构范式、特征提取方法、多元时间序列数据

## 1 Introduction

Time series are pervasive in various facets of our manufacture and life, serving as a primary dimension to record historical events. Forecasting, a critical task, leverages historical information within sequences to infer the future (Hyndman and Athanasopoulos, 2018; Petropoulos et al., 2022). It finds extensive applications in various domains closely intertwined with our lives, including energy production and consumption (Deb et al., 2017; Li et al., 2019b; Saxena et al., 2019; Rajagukguk et al., 2020; Zhao et al., 2016; Toubeau et al., 2018), meteorological variations (Mudelsee, 2019; Zaini et al., 2022), finance, stock markets, and econometrics (Sezer et al., 2020; Chen and Chen, 2015; Callot et al., 2017; Andersen et al., 2005; Luo et al., 2018; Kalra et al., 2024; Singh et al., 2023) sales and demand (Böse et al., 2017; Bandara et al., 2019) urban traffic flows (Tedjopurnomo et al., 2020; Lv et al., 2014; Li et al., 2017), and welfare-related healthcare conditions (Piccialli et al., 2021; Kaushik et al., 2020; Topol, 2019; Mishra et al., 2024).

Machine learning, data science, and other research groups employing operations research and statistical methods have extensively explored time series forecasting (Fuller, 2009; Faloutsos et al., 2018, 2019b,a). Statistical models typically consider non-stationarity, linear relationships, and specific probability distributions to infer future trends based on the statistical properties of historical data such as mean, variance, and autocorrelation. On the other hand, machine learning models learn patterns and rules from the data. With the emergence (Rosenblatt, 1957) and rapid development of deep learning (Goodfellow et al., 2016; LeCun et al., 2015), an increasing number of neural network models are being applied to time series forecasting. In contrast to the first two approaches that rely on domain-specific knowledge or meaningful feature engineering, deep learning autonomously extracts intricate time features and patterns from complex data. This capability enables the capture of long-term dependencies and complex relationships, ultimately enhancing prediction accuracy. In this article, we will refer to works on Deep Learning for Time Series Forecasting as DTSF works, and Time Series Forecasting will be abbreviated as TSF.

In recent years, deep learning methods have continuously advanced and innovated in time series forecasting (TSF) across various domains (Salinas et al., 2020; Xu et al., 2016; Lai et al., 2018; Bandara et al., 2020; Oord et al., 2016; Rasul et al., 2021; Lim et al., 2021). However, current research efforts primarily focus on key TSF concepts and fundamental model components, while lacking a high-level categorization of deep learning-based DTSF model structures, comprehensive summaries of recent developments, and in-depth analyses of future prospects and challenges. This article aims to address these gaps by drawing on the latest research. The main contributions of this work are as follows:

近年来，深度学习方法在时间序列预测（TSF）领域持续取得突破与创新（Salinas等, 2020; Xu等, 2016; Lai等, 2018; Bandara等, 2020; Oord等, 2016; Rasul等, 2021; Lim等, 2021）。然而现有研究主要聚焦于关键TSF概念与基础模型组件，缺乏对基于深度学习的DTSF模型结构的高层次分类、最新进展的系统性总结，以及未来前景与挑战的深度剖析。本文旨在借鉴最新研究成果填补这些空白，主要贡献如下：

• **Dynamic and systematic taxonomy.** We propose a novel dynamic classification method designed to categorize deep learning models for time series forecasting in a systematic manner. Our survey classifies and summarizes these models from the perspective of their architectural structure. To the best of our knowledge, this represents the first dynamic classification of deep learning model architectures for time series forecasting.

动态系统化分类体系。我们提出了一种创新的动态分类方法，旨在以系统化方式对时间序列预测的深度学习模型进行归类。本综述从模型架构结构的视角出发，对这些模型进行了分类与总结。据我们所知，这是首次针对时间序列预测的深度学习模型架构提出的动态分类体系

• **Comprehensive review of data feature enhancement.** We analyze and summarize feature enhancement methods for time series data, including dimensional decomposition, time-frequency transformation, pre-training, and patch-based segmentation. Our analysis begins with the composition of complex, high-dimensional data features, aiming to reveal the latent learning potential within time series data.

数据特征增强的全面综述。我们分析并总结了针对时间序列数据的特征增强方法，包括维度分解、时频变换、预训练以及基于分块的片段化处理。本分析从复杂高维数据特征的构成入手，旨在揭示时间序列数据中潜在的学习能力

• **Summary of challenges and future directions.** This survey summarizes major TSF datasets from recent years, discusses key challenges, and highlights promising future research directions to advance the field.

挑战与未来方向综述。本综述总结了近年来重要的时序预测数据集，探讨了该领域面临的关键挑战，并重点指出了推动学科发展的若干前瞻性研究方向

The remaining content is organized as follows. Section 2 introduces the fundamental aspects of TSF, encompassing the definition and composition of time series, forecasting tasks, statistical models, and existing problems. Section 3, a pivotal component of this paper, mainly delineates the overarching structural paradigm of DTSF models. Section 4 outlines the prevalent paradigms for extracting and learning features from time series data, constituting the second major focus. Section 5 is another key focus of this paper. We not only highlight the limitations and challenges within the current achievements in DTSF research but also elucidate prospective avenues for future exploration. Finally, we conclude this survey in Section 6. In Appendix A, an exhaustive account of TSF datasets across various domains is presented. Figure 1 shows an outline of the entire paper.

## 2 Time Series Forecasting

本文剩余内容安排如下：第二节阐述时间序列预测（TSF）的基础要素，包括时间序列的定义与构成、预测任务分类、统计模型框架及现存问题。第三节作为全文核心章节，系统阐述深度时间序列预测（DTSF）模型的总体架构范式。第四节详述时间序列数据特征提取与学习的通用范式，构成第二大研究重点。第五节是本文另一关键焦点，不仅剖析当前DTSF研究存在的局限性与挑战，同时展望未来研究的潜在发展方向。第六节为全文总结。附录A完整呈现跨领域TSF数据集详表，图1展示了全文的总体框架结构

Time series represents a continuous collection of data points recorded at regular or irregular time intervals, offering a chronological record of observed phenomena such as vital signs, sales trends, stock market prices, weather changes, and more. The nature of these observations can encompass numerical values, labels, etc. Moreover, time series can be either discrete or continuous (Hamilton, 2020). It is commonly employed for the analysis and prediction of trends and patterns (Montgomery et al., 2015) that evolve over time.

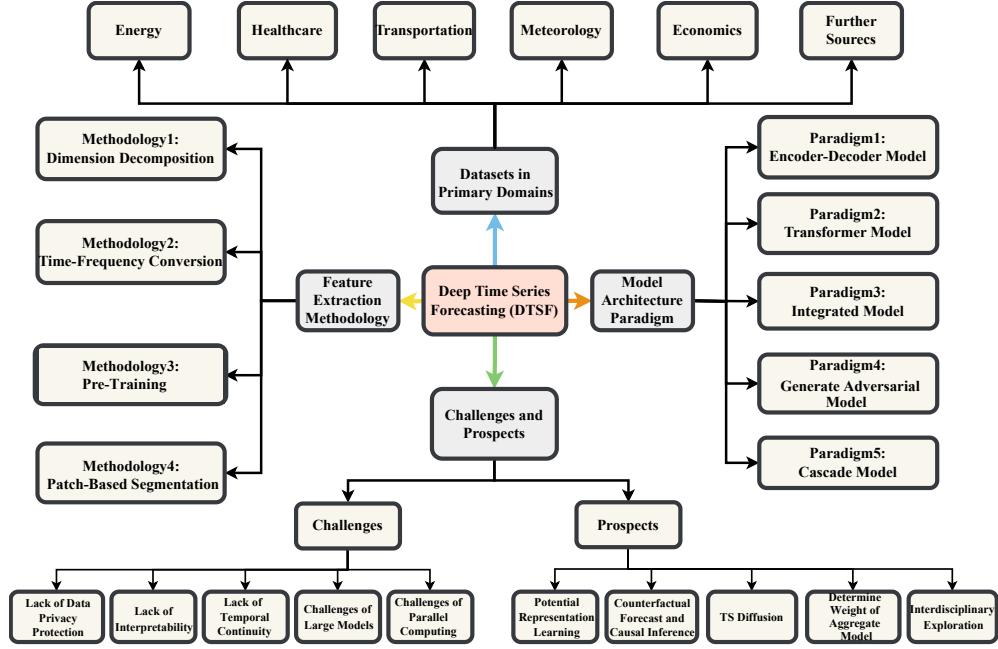
时间序列是指在规则或不规则时间间隔内记录的连续数据点集合，为生命体征、销售趋势、股票价格、天气变化等观测现象提供按时间顺序排列的记录。这些观测值的性质可包含数值型数据、标签型数据等。此外，时间序列既可以是离散的，也可以是连续的（Hamilton, 2020）。该方法通常用于分析和预测随时间演变的趋势与模式（Montgomery等, 2015）

TSF is the process of forecasting future values based on the inherent properties and characteristic patterns found in historical data. These properties and intrinsic patterns may provide valuable insights into describing future occurrences. Discovering potential features within time series data based on the similarity of statistical characteristics between adjacent data points or time steps is crucial for building a strong foundation for designing prediction models and achieving improved results.

时间序列预测（TSF）是指基于历史数据中固有的属性和特征模式来预测未来值的过程。这些属性和内在模式可为描述未来事件提供有价值的洞见。根据相邻数据点或时间步之间统计特征的相似性，发掘时间序列数据中的潜在特征，对于构建稳健的预测模型设计基础及获得优化结果具有关键意义

In this section, we will begin with the definition of time series and explain the concept of TSF. Furthermore, we will introduce classical methods based on mathematical

在本节中，我们将从时间序列的定义开始，并解释TSF的概念。此外，我们将介绍基于数理统计的经典方法。最后，我们将分析导致预测精度较低的因素，为该领域的研究人员提供初步的了解



**Fig. 1** The outline of this article

statistics. Lastly, we will analyze the factors contributing to lower prediction accuracy to provide researchers new to this field with a preliminary understanding.

## 2.1 Time Series Definition

在本综述中，我们将时间序列视为按时间顺序记录的观测序列，其观测点之间的时间间隔可以是固定或可变的。设  $t$  表示观测时间， $y_t$  代表时间序列，对于随时间观测到的随机变量所构成的随机过程。在大多数情况下， $t \in \mathbb{Z}$ ，其中  $\mathbb{Z} = (0, \pm 1, \pm 2, \dots)$  表示正负整数集合 (Fuller, 2009)。当仅能获取有限数据时，时间序列可表示为  $(y_1, y_2, y_3, \dots)$ 。令  $\mathcal{Y} = \{y_i, 1:T_i\}_{i=1}^N$  表示  $N$  条单变量时间序列的集合，其中  $y_{i,1:T_i} = (y_{i,1}, \dots, y_{i,T_i})$ ，而  $y_{i,t}$  代表第  $i$  条时间序列在  $t$  时刻的取值。 $y_{t1:t2}$  则是所有  $N$  条时间序列在时间区间  $[t_1, t_2]$  内取值的集合。

时间序列数据与其他类型的数据存在显著差异，因其普遍存在于所有主要领域，并作为构成现实世界的重要维度之一而具有特殊意义。这类数据具有广泛的属性和特征：首先，时间序列数据通常具有高噪声和高维特性，可采用降维技术、小波分析或滤波等方法消除部分噪声并降低维度 (Zebbari 等, 2020)；其次，采样时间间隔对其具有重要影响，由于现实世界中固有的不稳定性，不同采样频率下获得的时间序列分布并不具备统一的概率分布特征 (Yalavarthi 等, 2024)。

Time series data differs from other forms of data since it is prevalent in all major fields and is significant as one of the aspects that make up our reality. It has a wide range of attributes and characteristics. First of all, time series data are usually noisy and high-dimensional. Techniques such as dimensionality reduction, wavelet analysis, or filtering can be used to eliminate some noise and reduce dimensionality (Zebbari et al., 2020). Secondly, the sample time interval has an impact on it. Due to its inherent instability in reality, the distribution of time series obtained at different sampling frequencies does not have a uniform probability distribution (Yalavarthi et al., 2024).

Finally, if time series data is viewed as an information network, each time point can be considered a node, with the relationships between nodes evolving over time. Similar to most real-world networks, this data is inherently heterogeneous and dynamic (Peng et al., 2021), which presents significant challenges for the modeling and analysis of spatio-temporal data. It is worth noting that the representation of time series data is crucial for relevant features extraction and dimensionality reduction. The success or failure of model design and application is closely tied to this representation.

最后,若将时间序列数据视为信息网络,每个时间点可被视为一个节点,节点间的关系随时间动态演化。与大多数现实世界网络类似,此类数据本质上具有异质性和动态性(Peng等,2021),这为时空数据的建模与分析带来了重大挑战。值得注意的是,时间序列数据的表征对于相关特征提取与降维至关重要,模型设计与应用的成功与否与此表征密切相关。

## 2.2 Forecasting Task

TSF is a process of predicting future data based on historical observations, widely applied in various domains such as energy, finance, and meteorology to anticipate future trends. The task of TSF can be categorized into short-term and long-term forecasting based on the prediction horizon, which is determined by specific application requirements and domain characteristics. Short-term forecasting typically involves shorter time spans, often ranging from hours to weeks, emphasizing high prediction accuracy and is suitable for tasks demanding precision. In contrast, long-term forecasting spans longer periods, including months, years, or even longer durations, and addresses challenges related to long-term trends and seasonal variations that can significantly impact prediction accuracy. The distinction between these two types of forecasting lies in their specific emphasis. Short-term forecasting prioritizes precision and relies mainly on extrapolating data, suitable for scenarios where fluctuations within relatively short periods are critical for prediction outcomes. Conversely, long-term forecasting requires consideration of long-term trends and seasonal influences, making it more complex and necessitating additional factors such as extra assumptions and supplemental external data, which may affect its accuracy. Therefore, the role of external factors is particularly important in long-term forecasting, as they help the forecasting model better capture long-term trends, cyclical fluctuations, and other macro-level changes. For example, external factors such as weather, holidays, economic indicators, and road network information often have a significant impact on the trends and seasonal variations in time series data. Currently, many researchers have incorporated these external factors into forecasting models to improve the accuracy of predictions. Common approaches to handling external influences include incorporating external data as additional features into the model, using multi-task learning with external data (Ruder, 2017), and introducing exogenous variables into classical time series models. Deep learning methods, such as LSTM, GRU, and attention mechanisms, also enhance model performance by considering external factors (Qin et al., 2017). Additionally, seasonal adjustment, periodic modeling, and the integration of road network knowledge are effective methods for addressing external influences. For instance, MultiSPANS (Zou et al., 2024) uses a structural entropy minimization algorithm to generate optimal road network hierarchies, considering complex multi-distance dependencies in the road network for prediction; (Kong et al., 2024), in summarizing forecasting tasks, constructed a new bus station distance network to account for the relationships between external bus stations.

On the other hand, in addition to being categorized as Univariate (Zhang et al., 1998; Januschowski et al., 2020; Montero-Manso and Hyndman, 2021; Semenoglu

时间序列预测(TSF)是一种基于历史观测数据预测未来值的过程,其广泛应用于能源、金融、气象等诸多领域以实现趋势预判。根据预测周期的不同,TSF任务可分为短期预测与长期预测,这种划分取决于具体应用需求与领域特性。短期预测通常覆盖较短时间跨度(数小时至数周),强调预测精度的高要求,适用于对准确性敏感的预测场景;而长期预测则涉及更长时间范围(数月、数年甚至更长),需要应对可能显著影响预测准确性的长期趋势与季节性变化等挑战。两类预测的核心差异体现在关注重点上:短期预测以精度为优先,主要依赖数据外推法,适用于较短周期内波动对预测结果起决定性作用的场景;长期预测则需综合考量长期趋势与季节性影响,其复杂性更高,往往需要引入额外假设、补充外部数据等附加因素,这些因素可能对预测准确性产生影响。因此,外部因素在长期预测中具有特殊重要性,它们能帮助预测模型更好地捕捉长期趋势、周期波动等宏观变化。例如天气、节假日、经济指标、路网信息等外部因素,常对时间序列数据的趋势性与季节性变化产生显著影响。目前许多研究者已将此类外部因素纳入预测模型以提升精度,常见处理方法包括:将外部数据作为附加特征输入模型、采用外部数据驱动的多任务学习框架(Ruder, 2017)、在经典时间序列模型中引入外生变量等。深度学习方法(如LSTM、GRU和注意力机制)也通过融合外部因素来增强模型性能(Qin等, 2017)。此外,季节性调整、周期性建模以及路网知识融合均是应对外部影响的有效方法。典型案例例如:MultiSPANS(Zou等, 2024)采用结构熵最小化算法生成最优路网层级结构,通过考虑路网中复杂的多距离依赖关系进行预测;Kong等(2024)在总结预测任务时,构建了新型公交站点距离网络以刻画外部公交站点间的关联关系。

另一方面，除根据是否考虑多变量将时间序列预测划分为单变量预测（Zhang等, 1998; Januschowski等, 2020; Montero-Manso和Hyndman, 2021; Semenoglou等, 2021）与多变量预测（Lütkepohl, 2005; Kolassa, 2020）外，还可通过全局模型与局部模型的差异进行区分。单变量预测指预测过程中仅考虑单一变量的任务，其核心在于对单个变量未来值的预测；而多变量预测则需同时预测多个相关变量，通过考量变量间的相互依存关系来推断其未来值。在讨论单变量与多变量预测时，必须关注全局模型与局部模型的区别，这一差异直接影响建模方法及结果解读。全局模型会考虑整个时间序列数据集中的所有变量，而局部模型则聚焦于数据的特定子集（如特定区段或时间窗口），这种差异决定了数据内部依存关系的捕捉方式及预测结果的生成机制。

综上所述，预测任务的分类与侧重点取决于应用场景及需求。以金融领域为例，短期预测可能涉及对股价分钟级或小时级波动的预测，而长期预测则可能涵盖数周乃至数月的趋势研判。同理在气象学领域，短期预测或需关注数小时内天气变化，长期预测则可能针对数日乃至数周的天气系统演变。单变量预测可聚焦于特定产品的销量或单一股票的价格走势，而多变量预测则需同步推演多品类产品的销售态势或不同金融市场间的联动关系。

在后续章节中，我们将介绍统计预测模型并重点阐述其局限性，着重探讨传统时间序列预测方法所面临的挑战。随后，我们将深入分析深度学习预测模型与方法的发展历程。

统计预测模型的发展历程可追溯至20世纪初。如公式1与公式2所示，移动平均法（MA）（Box等, 2015; Hipel与McLeod, 1994; Cochrane, 1997）和简单指数平滑法（ES）（Gardner Jr, 1985）等最早的统计预测方法均建立在时间序列基础之上。

[et al., 2021](#)) and Multivariate (Lütkepohl, 2005; Kolassa, 2020) forecasting based on whether multiple variables are considered, TSF can also be distinguished by the distinction between global and local models. Univariate forecasting involves tasks where only one variable is considered during the forecasting process, primarily focusing on predicting the future values of a single variable. Multivariate forecasting, on the other hand, entails the simultaneous prediction of multiple correlated variables, considering the interdependencies among various variables and forecasting their future values. When discussing univariate and multivariate forecasting, it's essential to consider the distinction between global and local models, which impacts the modeling approach and the interpretation of results. Global models consider all variables across the entire time series dataset, while local models focus on subsets of the data, such as specific segments or windows, affecting how dependencies within the data are captured and predictions are made.

In summary, the categorization and focus of forecasting tasks depend on the application context and requirements. For instance, in the financial domain, short-term forecasting may involve predicting stock price fluctuations within minutes or hours, while long-term forecasting could encompass forecasts over several weeks or months. Similarly, in meteorology, short-term forecasting might entail predicting weather conditions within a few hours, while long-term forecasting may involve predictions spanning days or weeks. For univariate forecasting, the focus could be on forecasting the sales volume of a particular product or the price of a specific stock. On the other hand, multivariate forecasting might simultaneously predict the sales volumes of multiple products or the interrelationships within various financial markets.

In the following subsections, we will introduce statistical forecasting models and highlight their limitations, emphasizing the challenges posed by traditional TSF methods. Subsequently, we will delve into the development of deep learning forecasting models and methods.

### 2.3 Statistical Forecasting Model

The development history of statistical forecasting models can be traced back to the early 20th century. Equations 1 and 2 illustrate how the first statistical forecasting methods, such as Moving Averages (MA) ([Box et al., 2015; Hipel and McLeod, 1994; Cochrane, 1997](#)) and simple Exponential Smoothing (ES) ([Gardner Jr, 1985](#)), were based on time series.

$$MA_t(n) = \frac{1}{n} \sum_{i=t-n+1}^t x_i \quad (1)$$

其中， $n$ 为窗口大小， $MA$ 表示时间 $t$ 处的移动平均值  
where  $n$  is the window size, and  $MA$  represents the moving average at time  $t$ .

$$ES_{t+1} = \alpha \cdot x_t + (1 - \alpha) \cdot ES_t \quad (2)$$

其中， $ES_{t+1}$ 表示预测趋势， $\alpha$ 为平滑系数， $ES_t$ 代表上一时间步的预测值。移动平均法通过计算特定时间段内观测值的平均值来平滑数据，而指数平滑法则对近期观测值赋予更高权重，以反映数据的趋势特征。

where  $ES_{t+1}$  represents the predicted trend,  $\alpha$  is the smoothing coefficient, and  $ES_t$  is the value predicted at the previous time step. Moving average smooths data by calculating the average of observed values over a certain period of time, while exponential smoothing assigns higher weights to more recent observations to reflect the trend of the data.

Subsequently, the autoregressive (AR) (Box et al., 2015; Hipel and McLeod, 1994; Lee, 1994) and Moving Average (MA) models (represented by Equations 3 and 4, respectively) were introduced as two important concepts, leading to the development of the Autoregressive Moving Average Model (Box et al., 2015; Hipel and McLeod, 1994; Adhikari and Agrawal, 2013) (ARMA, as shown in equation 5). These models aim to accurately capture the auto correlation and averaging properties of time series data.

$$AR: Y_t = c + \varphi_1 Y_{t-1} + \varphi_2 Y_{t-2} + \cdots + \varphi_p Y_{t-p} + \xi_t \quad (3)$$

$$MA: Y_t = \mu + \epsilon_t + \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} + \cdots + \theta_q \epsilon_{t-q} \quad (4)$$

$$Y_t = c + \varphi_1 Y_{t-1} + \varphi_2 Y_{t-2} + \cdots + \varphi_p Y_{t-p} \\ + \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} + \cdots + \theta_q \epsilon_{t-q} + \epsilon_t \quad (5)$$

where  $Y_t$  represents the time series data under consideration,  $\varphi_1$  to  $\varphi_p$  are parameters of the AR model. These parameters describe the relationship between the current value and values from the past  $p$  time points. Similarly,  $\theta_1$  to  $\theta_q$  are parameters of the MA model, which describe the relationship between the current value and errors from the past  $q$  time points.  $\epsilon_t$  represents the error term at time  $t$ , and  $c$  denotes a constant term.

Specifically, the AR model leverages past time series observations to predict future values, while the MA model relies on the moving average of observations to make these predictions. To address non-stationary time series data, the Autoregressive Integrated Moving Average (ARIMA) model (Box et al., 2015; Hipel and McLeod, 1994; Cochrane, 1997; Hamzaçebi, 2008; Zhang, 2003) is introduced. ARIMA is employed to transform non-stationary sequences into stationary ones by means of differencing, thereby reducing or eliminating trends and seasonal variations in the time series. This transformation is represented by Equation (6) as follows:

$$\Delta Y_t = (1 - L)^d Y_t = \epsilon_t \quad (6)$$

where  $L$  denotes the lag operator,  $d$  represents the differencing order,  $y_t$  signifies the time series, and  $\epsilon_t$  is the error term. This integration of ARIMA helps mitigate non-stationarity, paving the way for more effective TSF.

Machine learning models represented by Random Forests and Decision Trees (Rokach, 2016; Ali et al., 2012; Ho, 1995; Kortschieder et al., 2015) offer enhanced flexibility and predictive performance in statistical forecasting (Harvey, 1990; Ahmed et al., 2010). A decision tree comprises a series of decision nodes and leaf nodes, constructed based on the selection of optimal features and splitting criteria to minimize prediction errors or maximize metrics like information gain or Gini index. Each decision node splits based on feature conditions, while each leaf node provides prediction results. Random Forest, on the other hand, makes forecasting by constructing multiple decision trees and combining their forecasting results. It can handle high-dimensional features and large-scale datasets, capturing nonlinear relationships and interactions between features.

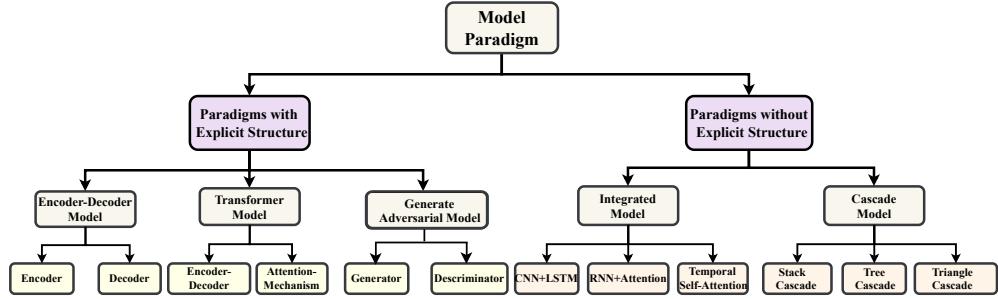
随后，自回归模型（Autoregressive, AR）(Box等, 2015; Hipel和McLeod, 1994; Lee, 1994)与移动平均模型（Moving Average, MA）(分别由公式3和公式4表示)作为两个重要概念被提出，由此发展出自回归移动平均模型（Box等, 2015; Hipel和McLeod, 1994; Adhikari和Agrawal, 2013）(ARMA, 如公式5所示)。这些模型旨在精确捕捉时间序列数据的自相关特性与平均特性。

其中， $Y_t$ 表示所研究的时间序列数据， $\varphi_1$ 至 $\varphi_p$ 为自回归模型(AR)的参数。这些参数描述了当前值与过去 $p$ 个时间点数值之间的关系。类似地， $\theta_1$ 至 $\theta_q$ 为移动平均模型(MA)的参数，用以表示当前值与过去 $q$ 个时间点误差项之间的关联。 $\epsilon_t$ 代表第 $t$ 时刻的误差项， $c$ 表示常数项。

具体而言，自回归(AR)模型利用时间序列的历史观测值预测未来数值，而移动平均(MA)模型则基于观测值的移动平均值进行预测。针对非平稳时间序列数据，研究者提出了自回归积分滑动平均(ARIMA)模型(Box等, 2015; Hipel与McLeod, 1994; Cochrane, 1997; Hamzaçebi, 2008; Zhang, 2003)。该模型通过差分运算将非平稳序列转化为平稳序列，从而有效削弱或消除时间序列中的趋势项与季节波动。这一转换过程可由公式(6)表示如下：

其中， $(L)$ 表示滞后算子， $(d)$ 表示差分阶数， $(y_t)$ 指代时间序列， $(\epsilon_t)$ 为误差项。通过ARIMA模型的这种积分处理，能够有效缓解非平稳性问题，从而为更高效的时间序列预测(TSF)奠定基础。

以随机森林和决策树为代表的机器学习模型(Rokach, 2016; Ali等, 2012; Ho, 1995; Kortschieder等, 2015)在统计预测领域展现出卓越的灵活性和预测性能(Harvey, 1990; Ahmed等, 2010)。决策树由一系列决策节点和叶节点构成，其构建过程基于最优特征与分割准则的选择，旨在最小化预测误差或最大化信息增益、基尼指数等指标。每个决策节点依据特征条件进行数据划分，而每个叶节点则输出预测结果。随机森林则通过构建多棵决策树并集成其预测结果进行推断，该算法能够有效处理高维特征和大规模数据集，并能捕捉特征间的非线性关系与交互作用。



**Fig. 2** The details of five paradigms

然而，物联网等新兴技术的发展为数据获取、采集与存储带来了效率提升和便利性（Li等, 2015; Kong等, 2022）。大数据时代已然来临 (Sagiroglu 和 Sinanc, 2013; Fan等, 2014)，数据正以日益增长的速率持续生成。统计预测模型需要更好地适应处理大规模高维数据的需求 (Che等, 2013; Wu等, 2013; Oussous等, 2018)。不同行业与领域对精准预测模型的需求也与日俱增，以支撑决策制定与规划实施 (Rodríguez-Mazahua等, 2016)。此外，实际应用中还面临着数据间更为复杂的关联关系，这要求模型具备更强的灵活性与精确性来应对这些挑战。

综上所述，传统统计预测模型在计算能力、预测精度及预测时长方面存在明显局限。该类方法在处理非平稳性、非线性关系、噪声干扰及复杂依赖关系时存在显著缺陷，对长期依赖性与多特征预测任务的适应性亦显不足。随着深度学习模型的持续发展与创新，上述局限性已被逐步突破，从而实现了预测性能的显著提升。

However, the development of emerging technologies such as the Internet of Things (IoT) has brought efficiency and convenience to data acquisition, collection, and storage (Li et al., 2015; Kong et al., 2022). The era of big data has arrived (Sagiroglu and Sinanc, 2013; Fan et al., 2014), with data being generated at an increasing rate. Statistical forecasting models need to better adapt to the demands of processing large-scale and high-dimensional data (Che et al., 2013; Wu et al., 2013; Oussous et al., 2018). Different industries and domains are also increasingly in need of accurate forecasting models to support decision-making and planning (Rodríguez-Mazahua et al., 2016). Furthermore, more complex relationships among data are encountered in practical applications, requiring more flexible and accurate models to tackle these challenges.

In summary, traditional statistical forecasting models are limited in terms of computational power, prediction accuracy, and length. There are major shortcomings in statistical forecasting methods in handling non-stationarity, nonlinear relationships, noise, and complex dependencies, and their adaptability to long-term dependencies and multi-feature forecasting tasks is also limited. With the continuous development and innovation of deep learning models, these limitations have been overcome, leading to improved predictive performance.

### 3 DTSF Model Architecture

时间序列数据普遍存在于能源、交通、通信系统等诸多现实领域。对时间序列数据进行精确建模与预测，对提升这些系统的运行效率具有关键作用。经典深度学习模型 (RNN、TCN、Transformer 和GAN) 在时间序列预测领域取得了显著进展 (Wu等, 2021; Zhou等, 2022b; Woo等, 2022b; Zhang等, 2022b)，为后续研究提供了重要参考。

广泛采用的方法之一是循环神经网络 (RNN)，它利用循环连接来处理时间关系并捕获序列数据中的演化模式。RNN的变体，即长短时记忆 (LSTM) 和门控循环单元 (GRU)，是专门为解决长期依赖性和有效捕获长时间序列中的模式而设计的。有很多基于RNN的研究，DeepAR (Salinas等人, 2020) 利用RNN和自回归技术来捕捉时间序列数据中的时间依赖性和模式。

Time series data is prevalent in various real-world domains, including energy, transportation, and communication systems. Accurately modeling and predicting time series data plays a crucial role in enhancing the efficiency of these systems. Classical deep learning models (RNN, TCN, Transformer, and GAN) have made significant advancements in TSF (Wu et al., 2021; Zhou et al., 2022b; Woo et al., 2022b; Zhang et al., 2022b), providing valuable insights for subsequent research.

One of the widely adopted methods is the Recurrent Neural Network (RNN), which utilizes recurrent connections to handle temporal relationships and capture evolving patterns in sequential data. Variants of RNNs, namely Long Short-Term Memory (LSTM) and Gated Recurrent Units (GRU), are specifically designed to address long-term dependencies and effectively capture patterns in long time series. There is a lot of research based on RNNs, DeepAR (Salinas et al., 2020) leveraged RNN and autoregressive techniques to capture temporal dependencies and patterns in time series

**Table 1** DTSF Model Architecture Paradigm

Architecture	Model	Multi/Uni	Output	Loss	Metrics	Year
Encoder - Decoder	COST (Woo et al., 2022a)	Multi & Uni	Point	contrastive loss	MSE, MAE	2022
	TS2Vec (Yue et al., 2022)	Multi & Uni	Point	contrastive loss	MSE	2022
	ACT (Li et al., 2022c)	Multi & Uni	Point	cross-entropy	Q50 loss, Q90 loss	2022
	SimTS (Zheng et al., 2023)	Multi & Uni	Point	cos-similarity loss, InfoNCE loss	MAE, MSE	2023
TFT	DeepTCN (Chen et al., 2020b)	Multi	Pro	quantile loss	NRMSE, SMAPE, MASE	2020
	STEP (Shao et al., 2022)	Multi	Pro	MAE	MAE, RMSE, MAPE	2022
	DCAN (He et al., 2022)	Multi	Point	RMSE	MAE, RMSE	2022
	FusFormer (Yang and Lu, 2022)	Multi	Point	-	RMSE, RMSE Decrease	2022
	HANet (Bi et al., 2023)	Multi	Point	-	MAE, RMSE	2022
	D <sup>3</sup> VAE (Li et al., 2022b)	Multi	Pro	-	MSE, CRPS	2022
	TI-MAE (Li et al., 2023b)	Multi	Point	MSE	MSE, MAE	2023
	AST (Wu et al., 2020b)	Uni	Pro	cross-entropy	Q50, Q90 loss	2020
	TFT (Lim et al., 2021)	Multi & Uni	Prob	quantile loss	P50, P90 quantile loss	2021
	Informex (Zhou et al., 2021)	Multi & Uni	Point	MSELoss	MSE, MAE	2021
	ETSformer (Woo et al., 2022b)	Multi & Uni	Point	MSELoss	MSE, MAE	2022
	FEDformer (Zhou et al., 2022b)	Multi & Uni	Point	MSELoss	MSE, MAE, Permutation	2022
Transformer	TACTiS (Drouin et al., 2022)	Multi & Uni	Pro	log-likelihood	CRPS-Sum, CRPS-means	2022
	Autoformer (Wu et al., 2021)	Multi & Uni	Point	L2 loss	MSE, MAE	2022
	NSTformer (Liu et al., 2022b)	Multi & Uni	Point	L2 loss	MSE, MAE	2023
	Dateformer (Young et al., 2022)	Multi & Uni	Point	MSE	MSE, MAE	2023
	Crossformer (Zhang and Yan, 2023)	Multi & Uni	Point	MSE	MSE, MAE	2023
	Scaleformer (Shabani et al., 2022)	Multi & Uni	Pro	MSE	MSE, MAE	2023
	BasisFormer (Ni et al., 2023)	Multi & Uni	Point	MSE	MSE, MAE	2023
	CRT (Zhang et al., 2022a)	Multi	Point	-	ROC-AUC, F1-Score	2021
	Pyraformer (Liu et al., 2021)	Multi	Point	MSE	MSE, MAE	2022
	TDformer (Zhang et al., 2022b)	Multi	Point	MSE	MSE, MAE	2022
	FusFormer (Yang and Lu, 2022)	Multi	Point	-	RMSE, RMSE Decrease	2022
GAN	Scaleformer (Shabani et al., 2022)	Multi	Point	MSE, Huber, Adaptive loss	MSE, MAE	2022
	Infomaxformer (Tang and Zhang, 2023)	Multi	Pro	MSELoss	MSE, MAE	2023
	PatchTST (Nie et al., 2022)	Multi	Point	Adaptive Loss	MSE, MAE	2023
	iTransformer (Liu et al., 2023c)	Multi	Point	L2 Loss	MSE, MAE	2023
	MCformer (Han et al., 2024)	Multi	Point	MSE, MAE	MSE, MAE	2024
	SAMformer (Ilbert et al., 2024)	Multi	Point	MSE	MSE, MAE	2024
	TSLANet (Eldele et al., 2024)	Multi	Point	MSE	MSE, MAE	2024
	MASTER (Li et al., 2024a)	Multi	Point	MSE	IC, ICIR, RankIC	2024
	TimeSiam (Dong et al., 2024)	Multi	Point	L2, Cross-Entropy	MSE, MAE, Recall, F1 Score	2024
	Chronos (Ansari et al., 2024)	Multi	Point	Cross Entropy	WQL, CRPS, MASE	2024
	TimeXer (Wang et al., 2024c)	Multi	Point	L2 loss	MSE, MAE	2024
Integrated Module	Time-SSM (Hu et al., 2024)	Multi	Point	MSE	MSE, MAE	2024
	SageFormer (Zhang et al., 2024)	Multi	Point	MSE	MSE, MAE	2024
	TIME-LLM (Wang et al., 2024a)	Multi	Point	MSE, SMAPE	MSE, MAE, SMAPE	2024
	CARD (Wang et al., 2024b)	Multi	Point	MSE, MAE	MSE, MAE	2024
	Pathformer (Chen et al., 2024)	Uni	Pro	L1 loss	MSE, MAE	2024
	ForGAN (Koochali et al., 2019)	Multi & Uni	Pro	RMSE	MAE, MAPE, RMSE	2019
	COSCI-GAN (Seyfi et al., 2022)	Multi & Uni	Pro	Global loss = local + central	MAE	2022
	RCGAN (Esteban et al., 2017)	Multi	Pro	cross-entropy	AUROC, AUPRC	2017
	TimeGAN (Yoon et al., 2019)	Multi	Pro	Unsupervised, Supervised, Reconstruction, Loss	Discriminative and Predictive Score	2019
	PSA-GAN (Jeha et al., 2022)	Multi	Point	Wasserstein loss	-	2022
	AEC-GAN (Wang et al., 2023)	Multi	Point	MSE	ACF, Skew / Kurt, FD	2023
Cascade	ITF-GAN (Klopries and Schwung, 2024)	Multi	Point	MSE	MSE, STS, Pearson, Hellinger, Pred.	2024
	MAGAN (Ferchichi et al., 2024)	Multi	Point	-	MAE, MAPE	2024
	TSGAN (Xu et al., 2024)	Multi	Point	-	MAE, RMSE, MAPE	2022
	AST (Wu et al., 2020b)	Uni	Pro	cross-entropy	Q50 loss, Q90 loss	2020
	ConvLSTM (Shi et al., 2015)	Multi & Uni	Point	cross-entropy	Rainfall-MSE, CSI, FAR, POD	2015
	Bi-LSTM (Du et al., 2020)	Multi	Point	MSE	MAE, RMSE	2020
	(Fu et al., 2022a)	Multi	Point	MAE	MAE, RMSE, MAPE	2022
	(Asif et al., 2018)	Uni	Point	L2 loss	MAE, MSE, MAPE	2018
	TATCN (Wang and Zhang, 2022)	Uni	Point	-	MAE, RMSE, sMAPE	2022
	LST-TCN (Sheng et al., 2022)	Uni	Point	Pinball loss	MAPE, RMSE	2022
	TimesNet (Wu et al., 2022)	Multi & Uni	Point	MSE, SMAPE	MSE, MAE, SMAPE, MASE	2022
	TreeDRNeT (Zhou et al., 2022c)	Multi & Uni	Point	Lp Regularized Loss	MSE, MAE	2022
Others	Triforner (Cirstea et al., 2022)	Multi & Uni	Point	-	MSE, MAE	2022
	SCINet (Liu et al., 2022a)	Multi & Uni	Point	L1 loss	RSE, CORR, MSE, MAE, MAPE, RMSE	2022
	HTSF (Duan et al., 2023)	Multi	Pro	L2 loss, HyperGRU	MAE, RMSE	2023
	CIPM (Yolcu and Yolcu, 2023)	Multi	Point	-	RMSE, MAPE, MdRAE	2023
	MACN (He et al., 2023)	Multi	Point	RMSE	RMSE, MAE	2023
	CasCIFF (Zhu et al., 2024)	Multi	Point	-	MSLE, MAPE	2024
	FCPM (Guo et al., 2024)	Multi	Point	RMSE	MAE	2024
	N-BEATS (Oreshkin et al., 2019)	Uni	Point	MAE	SMAPE, OWA, MASE	2020

MQRNN (Wen等人, 2017年) 通过融合循环神经网络的表达力与时序特性、分位数回归的非参数特性以及直接多步预测的高效性, 提出了一种名为“分叉序列”的新型训练方案, 显著提升了模型的稳定性与预测性能。ES-RNN (Smyl, 2020年) 则构建了一个动态计算图神经网络框架, 将标准指数平滑模型与长短期记忆网络整合于统一体系之中。

除循环神经网络外, 卷积神经网络 (CNN) 同样可应用于时间序列预测任务。通过将时间序列数据视为一维信号进行处理, 卷积神经网络能够从局部区域提取特征, 从而有效捕捉局部模式并保持平移不变性。值得注意的是, 时序卷积网络 (TCN) 是基于卷积神经网络的时间序列分析模型中具有代表性的范例。

时态卷积网络 (Temporal Convolutional Network) 是一种经典深度学习模型, 因其能有效捕捉长程依赖关系而在时间序列预测领域广受关注。与传统循环神经网络不同, 该模型采用带有空洞卷积的卷积层结构, 可在不增加参数量的前提下扩展感受野。这种特性使时态卷积网络在保持计算效率的同时, 能更高效地处理长程依赖问题 (Bai等, 2018a)。对于具有复杂时间模式的序列数据, 该模型能有效建模不同长度的时序关系, 且不会出现梯度消失问题 (Deng等, 2019)。在交通流量预测中, 该技术已成功应用于传感器数据的时间依赖性建模, 实现了高精度的交通状况预测 (Zhao等, 2019)。值得注意的是, 当与注意力机制、特征提取层等技术结合时, 时态卷积网络在各类型预测任务中展现出更优越的性能。例如, 在电力负荷预测、能源需求预测等多变量时间序列预测任务中, 基于注意力机制增强的时态卷积网络模型取得了显著提升的预测效果。总体而言, 该模型为时间序列预测提供了强大而高效的解决方案, 尤其适用于处理长序列或具有复杂时间依赖性的数据集。

另一种有价值的技法是注意力机制, 该机制使模型能够对输入序列的不同部分赋予差异化权重。这一特性尤其有利于处理长期序列或在特定时间节点聚焦关键信息。此外, 生成对抗网络 (GAN) 也可应用于时间序列预测领域。通过生成器与判别器之间的对抗训练, 生成对抗网络能够合成时间序列样本, 从而提供更精确的预测结果。

在本节中, 我们基于模型架构维度对现有时间序列模型进行动态分类。研究聚焦于模型的内部结构设计, 将五种模型架构划分为显式结构范式与隐式结构范式两类。图2展示了我们提出的模型分类方案的更多细节。表1全面汇总了近年来做出突出贡献的各类模型, 表2则精选若干关键模型, 就其优势、缺陷、应用领域及预测范围展开详细解析。此举旨在帮助读者理解各模型的独特性, 并为特定预测任务选择最适配模型提供指导。

MQRNN (Wen et al., 2017) exploited the expressiveness and temporal nature of RNNs, the nonparametric nature of Quantile Regression and the efficiency of Direct Multi Horizon Forecasting, proposed a new training scheme named forking-sequences to boost stability and performance. ES-RNN (Smyl, 2020) proposed a dynamic computational graph neural network with a standard exponential smoothing model and LSTM in a common framework.

In addition to RNNs, Convolutional Neural Networks (CNNs) can also be employed for TSF. By processing time series data as one-dimensional signals, CNNs can extract features from local regions, enabling them to capture local patterns and translational invariance effectively. Notably, Temporal Convolutional Networks (TCNs) represent a prominent example of CNN-based models for time series analysis.

The Temporal Convolutional Network is a classical deep learning model that has garnered widespread attention in time series forecasting due to its ability to effectively capture long-range dependencies. Unlike traditional RNN, TCNs employ convolutional layers with dilated convolutions to expand the receptive field without increasing the number of parameters. This enables TCNs to handle long-range dependencies more efficiently while maintaining computational efficiency (Bai et al., 2018a). TCNs are particularly useful for time series data with complex temporal patterns, as they can model sequences of varying lengths without suffering from the vanishing gradient problem (Deng et al., 2019). In traffic flow prediction, TCNs have been successfully applied to model the temporal dependencies in sensor data, achieving high accuracy in forecasting traffic conditions (Zhao et al., 2019). Furthermore, when combined with other techniques such as attention mechanisms and feature extraction layers, TCNs have demonstrated improved performance across various prediction tasks. For instance, integrating TCNs with attention-based models has shown enhanced results in multivariate time series forecasting tasks like electricity load prediction and energy demand forecasting. Overall, TCNs provide a powerful and effective approach to time series forecasting, especially when dealing with long sequences or datasets with complex temporal dependencies.

Another valuable technique is the attention mechanism, which allows models to assign varying weights to different parts of the input sequence. This is particularly beneficial for handling long-term series or focusing on important information at specific time points. Additionally, Generative Adversarial Networks (GANs) can be utilized for TSF. Through adversarial training between a generator and a discriminator, GANs can generate synthetic time series samples and provide more accurate prediction results.

In this section, we dynamically classify existing time series models based on the model architecture dimension. We focus on the internal structural design of the models and categorize the five model architectures into explicit structure paradigms and implicit structure paradigms. Figure 2 shows more details of our proposed model classification. Table 1 comprehensively summarizes the models that have made outstanding contributions in recent years. Table 2 selects several key models and provides a detailed analysis of their advantages, disadvantages, application domains, and prediction horizons. The aim is to help readers understand the unique characteristics of each model and guide them in selecting the most suitable model for specific prediction tasks.

### 3.1 Model with Explicit Structure

#### 3.1.1 Encoder-Decoder Model

The encoder-decoder model is widely used in the field of deep learning, which appears similar to seq2seq and has an explicit encoder and a decoder. However, seq2seq seems to be described from an application-level perspective, while the encoder-decoder is described at the network level. U-net for medical image segmentation ([Ronneberger et al., 2015](#)) and various forms of Transformers are well-known applications.

编码器-解码器模型在深度学习领域应用广泛，其结构与序列到序列（seq2seq）模型相似，均包含显式的编码器和解码器模块。然而，序列到序列模型通常是从应用层面进行描述，而编码器-解码器模型则更多在网络架构层面进行讨论。医学图像分割中的U-Net网络（Ronneberger等, 2015）以及各类Transformer变体，都是该模型的典型应用实例

**Table 2** A comparative analysis of time series forecasting models: advantages, disadvantages, applications, and prediction lengths. 时间序列预测模型的比较分析：优势、劣势、应用场景及预测长度

Model	Advantages	Disadvantages	Applications	Prediction Horizon
Informer ( <a href="#">Zhou et al., 2021</a> )	Effcient; Strong representation; Good generalization	Sensitive to data shifts	Energy; Weather	Long
HANet ( <a href="#">Bi et al., 2023</a> )	Capture complex dependencies; Flexible for multivariate data	High complexity	Weather; Ecology	Long
Autoformer ( <a href="#">Wu et al., 2021</a> )	Efficient; Good information	High complexity; Depend on data periodicity	Finance; Energy; Electricity; Traffic; Weather; Healthcare	Long
ETSformer ( <a href="#">Woo et al., 2022b</a> )	Combine traditional methods with Transformer; Adaptive time window	High computational cost; Requires large data	Finance; Energy; Electricity; Traffic; Weather; Healthcare	Short
FEDformer ( <a href="#">Zhou et al., 2022b</a> )	Frequency enhancement; Better flexibility for long-term forecasts	High complexity; Large data needed	Finance; Energy; Electricity; Traffic; Weather; Healthcare	Long
TreeDRNet ( <a href="#">Zhou et al., 2022c</a> )	Capture time dynamics; Efficient training with joint networks	High complexity; Need large data.	Finance; Energy; Electricity; Traffic; Weather; Healthcare	Long
TATCN ( <a href="#">Wang and Zhang, 2022</a> )	Capture temporal dependencies; Extract local patterns.	High computational cost; Data dependence.	Electricity; Healthcare	Short

In this context, the classic Seq2Seq model stands as one of the most representative Encoder-Decoder architectures. It uses Long Short-Term Memory networks as both the encoder and decoder to map input sequences to output sequences, making it particularly suitable for multi-step forecasting tasks ([Sutskever, 2014](#)). Additionally, LSTM and GRU are classic models for time series data modeling, capable of capturing long-term dependencies, and have demonstrated excellent performance in various time series forecasting tasks, such as financial forecasting and weather prediction ([Cho,](#)

在此背景下，经典的Seq2Seq模型是最具代表性的编码器-解码器架构之一。该模型采用长短期记忆网络同时作为编码器和解码器，将输入序列映射至输出序列，使其特别适用于多步预测任务（Sutskever, 2014）。此外，LSTM和GRU作为时间序列数据建模的经典模型，能够捕捉长期依赖关系，并在金融预测、气象预报等多种时间序列预测任务中展现出卓越性能（Cho, 2014）。与传统RNN不同，时序卷积网络（TCN）通过卷积层处理长期依赖问题，在交通流量预测、气象预报等应用中取得显著效果（Bai等, 2018a）。而双向编码器-解码器模型利用双向LSTM同时捕获历史与未来时间信息，进一步提升了模型的预测精度（Cheng等, 2022）。这些经典编码器-解码器模型凭借其自动学习时间序列复杂模式的能力，已成为时间序列预测任务中不可或缺的工具。

2014). In contrast to traditional RNNs, TCN leverage convolutional layers to address long-term dependency issues, achieving strong results in several time series forecasting applications, particularly in traffic flow prediction and weather forecasting (Bai et al., 2018a). Moreover, the Bi-directional Encoder-Decoder model, which utilizes bidirectional LSTM, captures both past and future time information, further enhancing the model's forecasting accuracy (Cheng et al., 2022). These classic Encoder-Decoder models, with their ability to automatically learn complex patterns in time series data, have become essential tools in time series forecasting tasks.

编码器-解码器架构在时间序列预测 (TSF) 领域同样得到了广泛且成功的应用。例如, Perslev 等人 (2019) 受 U-Net (Ronneberger 等, 2015) 启发, 基于 U型网络架构设计了一种名为 U-Time 的全卷积时序网络。该网络能够将任意长度的序列输入映射至用户自定义时间尺度上的标签序列, 其整体结构呈现高度对称的编码器-解码器 U型拓扑。我们认为这种高度对称性的设计源于网络输入与输出存在于同一空间域的特性: 编码器将输入映射至另一空间后, 解码器需从该空间进行逆向映射还原, 因此从理论层面决定了网络架构必须具备高度对称性。

Encoder-decoder has also been extensively and successfully applied in the field of TSF. For instance, Perslev et al. (2019) was inspired by U-net (Ronneberger et al., 2015) and designed a time fully convolutional network called U-Time based on the U-net architecture. U-Time maps arbitrarily long sequential inputs to label sequences on a freely chosen time scale. The overall network exhibits a U-shaped architecture with highly symmetric encoder and decoder components. We believe that the high degree of symmetry in the architecture is because the proposed network's input and output exist in the same space. The encoder maps the input into another space, and the decoder should map back from this space. Therefore, the network architecture is theoretically highly symmetric.

存在诸多高度对称的编码器-解码器网络架构, 同时也存在编码器与解码器不对称的案例。最具代表性的当属 Transformer 架构 (Zhou 等, 2021; Wu 等, 2021; Zhou 等, 2022b; Yang 与 Lu, 2022)。可观察到解码器不仅与编码器存在差异, 还需接收特定输入。这种编码器-解码器架构被认为需要辅助额外信息才能实现更优性能。

There are many highly symmetric encoder-decoder network architectures, as well as cases where the encoder and decoder are asymmetric. The most typical example is the Transformer architecture (Zhou et al., 2021; Wu et al., 2021; Zhou et al., 2022b; Yang and Lu, 2022). It can be observed that the decoder differs from the encoder and receives input. This encoder-decoder architecture is considered to require additional information for assistance to perform better.

同样地, Guo 等学者 (2023) 提出了一种非对称编码器-解码器学习框架, 该框架通过卷积神经网络和门控循环神经网络提取多栋建筑间的空间关系与时间序列特征, 从而在编码器中形成新的输入数据。解码器则借助注意力机制基于这些输入数据进行预测。

Likewise, Guo et al. (2023) proposed an asymmetric encoder-decoder learning framework where the spatial relationships and time-series features between multiple buildings are extracted by a convolutional neural network and a gated recurrent neural network to form new input data in the encoder. The decoder then makes predictions based on the input data with an attention mechanism.

此外还存在其他编码器-解码器架构的例证。Bi 等人 (2023) 提出了一种用于多元时间序列长期预测的新型分层注意力网络 (HANet), 该架构同样包含编码器与解码器模块。然而值得注意的是, 其编码器与解码器结构存在显著差异, 即二者呈现非对称特性。此外, 某些网络架构虽明确包含编码器组件, 却未设置显式的解码器模块 (Eldele 等人, 2021年)。

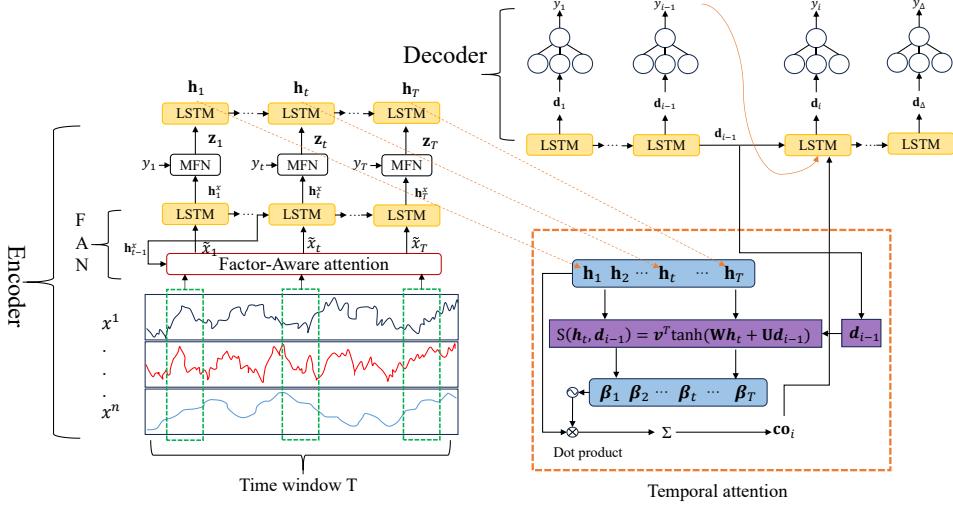
There are some other examples of encoder-decoder here as well. In Bi et al. (2023), a novel hierarchical attention network (HANet) for the long-term prediction of multivariate time series was proposed, which also includes an encoder and a decoder. However, the encoder and decoder architectures are noticeably different. That is to say, the encoder and decoder are asymmetric. There are also network architectures that explicitly involve an encoder but lack an explicit decoder (Eldele et al., 2021).

### 3.1.2 Transformer Model

随着Transformer在计算机视觉和自然语言处理 (NLP) 领域的卓越表现, 该模型也被应用于时间序列预测 (TSF) 领域并展现出巨大潜力。Transformer 的核心架构主要由注意力机制和编码器-解码器结构构成。

With the remarkable performance of Transformer in computer vision and Natural Language Processing (NLP) domains, they have also been applied to the field of TSF and have shown great promise. The main architecture of the Transformer includes the attention mechanism and the encoder-decoder architecture.

However, applying Transformer to TSF tasks is not without challenges and limitations. Recent studies have highlighted several issues, such as the inability to directly handle Long Sequence Time Forecasting (LSTF), including quadratic time

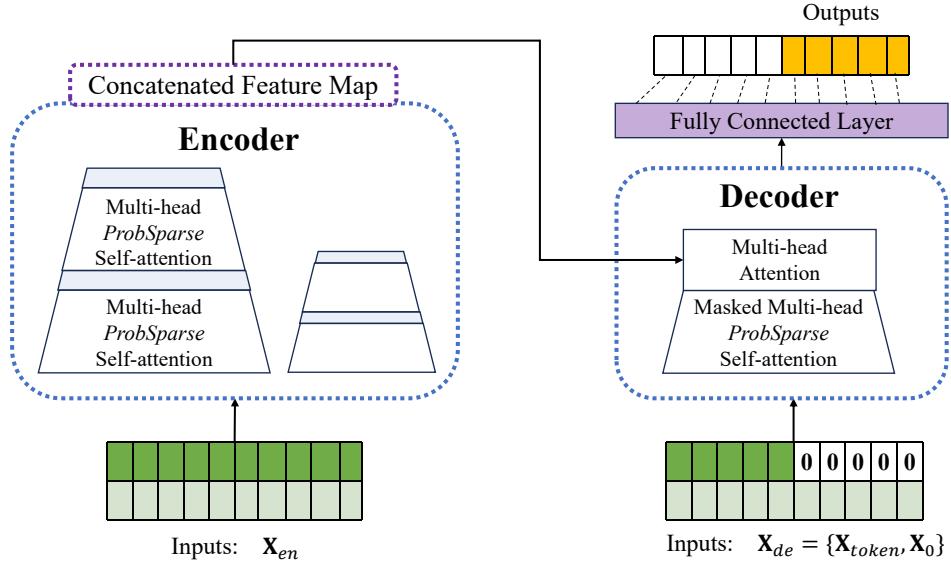


**Fig. 3** The overview of HANet model

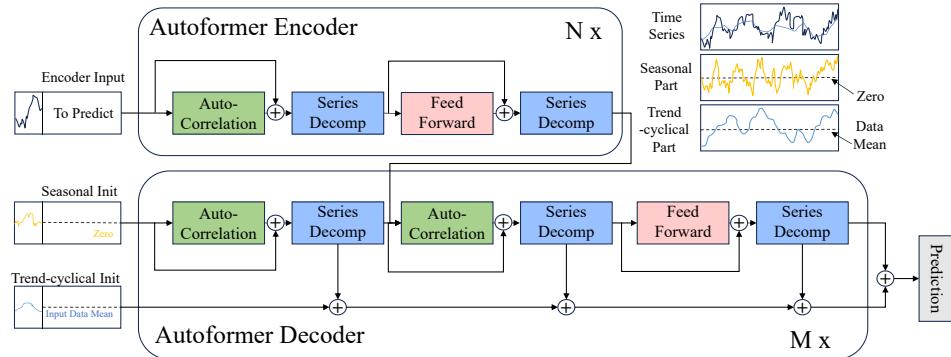
complexity, high memory usage, and inherent limitations of the encoder-decoder architecture. To address these limitations, Informer (Zhou et al., 2021) was an efficient Transformer-based architecture specifically designed for LSTF. This architecture utilizes the ProbSparse self-attention mechanism, which reduces the time complexity and memory usage to  $O(L \log L)$ . From the network architecture perspective, it is evident that Informer's architecture (Zhou et al., 2021) closely resembles the vanilla Transformer, consisting of an encoder and a decoder. The encoder receives the input, and the decoder receives the output from the encoder as well as the input, with the addition of zero-padding in the parts to be predicted. The self-attention mechanism is replaced with the ProbSparse self-attention mechanism. TFT (Lim et al., 2021) proposed other architectural improvements to improve accuracy and computational complexity, which integrates high-performance multi-horizon forecasting with interpretable insights into temporal dynamics, capturing temporal relationships at different scales by employing recurrent layers for local processing and interpretable self-attention layers for long-term dependencies.

Autoformer (Wu et al., 2021), on the other hand, argues that previous Transformer-based prediction models (e.g., Informer (Zhou et al., 2021)) mainly focused on improving self-attention for sparse versions. While significant performance improvements were achieved, they sacrificed the utilization of information. One of the reasons why Transformer cannot be directly applied to LSTF is the complex characteristics of time series data. Without special design, traditional attention mechanisms struggle to model and learn these characteristics. Autoformer (Wu et al., 2021) adopts decomposition as a standard approach for time series analysis (Makridakis, 1978; Cleveland et al., 1990), as it is believed that decomposition can untangle the intertwined time patterns and highlight the intrinsic properties of time series. Autoformer (Wu et al., 2021) introduces a novel decomposition architecture with autocorrelation mechanisms,

然而, 将 Transformer 应用于时间序列预测 (TSP) 任务并非没有挑战和局限性。近期研究指出了几个问题, 例如其无法直接处理长序列时间预测 (LSTF), 这包括二次时间计算复杂度、高内存消耗, 以及编码器-解码器架构固有的局限性。为应对这些局限性, Informer (Zhou et al., 2021) 提出了一种专为 LSTF 设计的高效基于 Transformer 的架构。该架构采用了 ProbSparse 自注意力机制, 将时间复杂度和内存消耗降至  $O(L \log L)$ 。从网络架构角度看, 显然 Informer (Zhou et al., 2021) 的架构非常类似于原始 (vanilla) Transformer, 由一个编码器和一个解码器组成。编码器接收输入, 解码器则接收来自编码器的输出以及输入本身, 并对需要预测的部分进行零填充。其自注意力机制被替换为 ProbSparse 自注意力机制。另一方面, TFT (Lim et al., 2021) 提出了其他架构改进以提高预测精度和降低计算复杂度。它将高性能的多水平预测与对时间动态模式的可解释性洞察相结合, 通过采用循环层进行局部处理、并使用可解释的自注意力层捕获长期依赖关系, 从而捕捉不同时间尺度上的时序关系。另一方面, Autoformer (Wu et al., 2021) 提出, 以往基于 Transformer 的预测模型 (例如 Informer (Zhou et al., 2021)) 主要集中于改进稀疏化版本的自注意力机制。虽然取得了显著的性能提升, 但它们牺牲了信息的利用效率。Transformer 无法直接应用于长序列时间预测 (LSTF) 的原因之一在于时间序列数据的复杂性。若缺乏专门设计, 传统的注意力机制难以建模和学习这些特性。因此, Autoformer (Wu et al., 2021) 采用分解作为时间序列分析的标准方法 (Makridakis, 1978; Cleveland et al., 1990), 因为人们认为分解能够理清相互交织的时间模式, 并突出时间序列的内在属性。Autoformer (Wu et al., 2021) 引入了一种结合自相关机制的全新分解架构, 这与传统的序列分解预处理方法不同。在网络架构方面, 其遵循与 Transformer、Informer 及其他类似架构相似的宏观架构。区别在于解码器 (Decoder) 的输入不再是原始输入, 而是通过时间序列分解得到的子序列, 这些子序列包含季节性和趋势性维度。



**Fig. 4** The overview of Informer model



**Fig. 5** The overview of Autoformer model

which is different from the conventional series decomposition preprocessing. In terms of the network architecture, it follows a macro architecture similar to Transformers, Informer, and other architectures. The difference lies in the input to the Decoder, which is no longer the original input but rather sub-sequences obtained through time series decomposition, including seasonal and trend dimensions.

In time series forecasting tasks, many researchers prefer to divide long time series into smaller segments to help Transformer models focus more effectively on local temporal features. This approach enhances the model's ability to learn local patterns while

在时间序列预测任务中，许多研究者倾向于将长序列分割为较短的片段，以帮助Transformer模型更有效地聚焦局部时序特征。这种方法在增强模型局部模式学习能力的同时，还能降低计算负担。TSMixer（Ekambaram等人，2023）采用了类似策略，将时序数据划分为多个补丁后，通过基于MLP的层级结构处理这些补丁以提取特征。这种与计算机视觉中基于补丁的方法相仿的处理方式，使模型在时序预测任务中既能有效捕捉局部特征，又可降低计算复杂度和内存需求。Zhang等人（2023b）在其研究MTPNNet中提出了一种新型的基于Transformer的多变量时序建模方法，通过对时序分解补丁的季节性成分同时进行时间和空间维度的嵌入，实现了任意粒度时序信息的建模。

reducing computational burden. TSMixer (Ekambaram et al., 2023) adopts a similar strategy by partitioning time series data into multiple patches and then processing these patches through MLP-based layers to extract features. This approach, akin to patch-based methods in computer vision, enables the model to capture local features effectively while reducing computational complexity and memory requirements in time series forecasting tasks. Zhang et al. (2023b) proposed a novel Transformer-based multivariate time series modeling approach in their work, MTPNet. It achieves modeling of temporal information at arbitrary granularities by simultaneously embedding temporal and spatial dimensions of the Seasonal part of the time series decomposition patches.

There are further works addressing Transformers in the context of TSF. ETSformer (Woo et al., 2022b) argues that the sequence decomposition used by Autoformer makes simplified assumptions and is insufficient to properly model complex trend patterns. Considering that seasonal patterns are more easily identifiable and detectable, ETSformer designs exponential smoothing attention (ESA) and frequency attention (FA) mechanisms. The network architecture decomposes the time series into interpretable sequence components such as level, growth, and seasonality. FEDformer combines Transformers with seasonal-trend decomposition methods. The decomposition method captures the global profile of the time series, while the Transformer captures more detailed architectures, making it a frequency-enhanced Transformer.

These studies demonstrate the ongoing efforts in leveraging Transformers for TSF and the development of specialized architectures and mechanisms to overcome the challenges and limitations associated with applying Transformers to this domain.

在时间序列预测 (TSF) 领域，针对 Transformer 模型的研究持续深入。ETSformer (Woo 等人, 2022b) 指出 Autoformer 采用的序列分解方法存在简化假设，难以充分建模复杂趋势模式。鉴于季节性模式更易识别和检测，该研究设计了指数平滑注意力 (ESA) 和频率注意力 (FA) 机制，其网络架构可将时间序列分解为可解释的组成部分，如水平项、增长项和季节性项。FEDformer 则将 Transformer 与季节性-趋势分解方法相结合：分解模块负责捕捉时间序列的全局轮廓，而 Transformer 结构则专注于更精细的特征建模，由此构建出频率增强型 Transformer 架架。

这些研究表明，学界正持续致力于利用 Transformer 模型进行时间序列预测，并通过开发专用架构与机制来克服该领域应用 Transformer 所面临的挑战与局限性。

### 3.1.3 Generative Adversarial Model

GAN (Generative Adversarial Networks) has attracted significant attention since its introduction as a generative model consisting of an explicit structure including a discriminator and a generator. While GANs have been widely used in the field of computer vision, their application in TSF has been relatively limited. The reason for this limited usage is speculated to be the availability of alternative metrics such as CRPS (Continuous Ranked Probability Score) that can measure the quality of generated samples (Benidis et al., 2022).

生成对抗网络 (GAN) 自提出以来便因其由判别器与生成器构成的显式结构而作为生成模型受到广泛关注。尽管 GAN 在计算机视觉领域已得到普遍应用，但在时间序列预测 (TSF) 中的应用仍相对有限。据推测，这种局限性源于存在诸如连续排序概率评分 (CRPS) 等衡量生成样本质量的替代性评估指标 (Benidis 等, 2022)

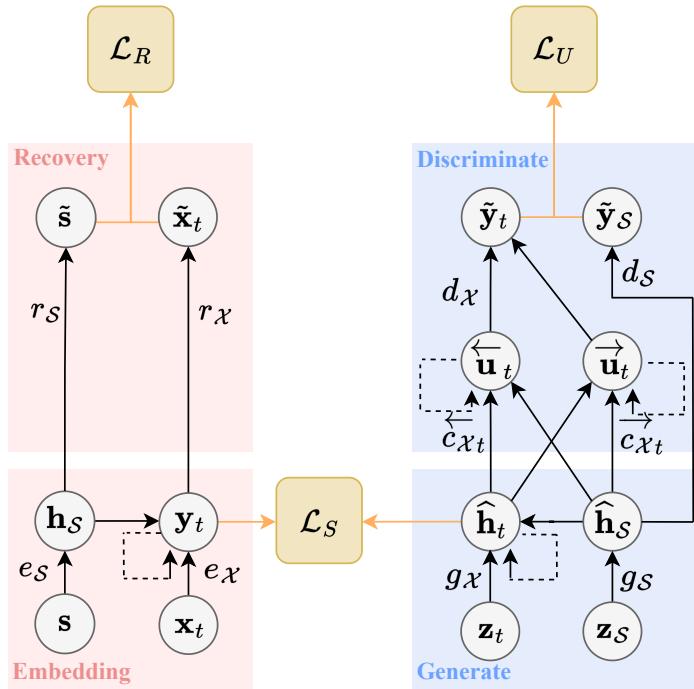
In the existing literature on GAN-based TSF, most studies focus on generating synthetic time series datasets (Yoon et al., 2019; Esteban et al., 2017; Takahashi et al., 2019). The discriminator is trained to distinguish between real and generated time series data, with the goal of producing synthetic data that is indistinguishable from real data. TimeGAN (Yoon et al., 2019), a GAN-based network architecture, was proposed to generate realistic time series data by leveraging the flexibility of unsupervised models and the control of supervised models. It utilizes an embedding function and a recovery function to extract high-dimensional features from time series data, which are then fed into the sequence generator and sequence discriminator for adversarial training. Another study proposed a GAN-based network architecture using Recurrent Neural Networks (RNNs) to generate real-valued multidimensional time series (Takahashi et al., 2019). The study introduced two variations, Recursive GAN (RGAN) and Recursive Conditional GAN (RCGAN), where RGAN generates real-valued data

在有关于基于生成对抗网络的时间序列生成 (GAN-based TSF) 的文献中，大多数研究集中于生成合成时间序列数据集 (Yoon 等, 2019; Esteban 等, 2017; Takahashi 等, 2019)。判别器通过区分真实时间序列数据与生成数据来进行训练，其目标是产生与真实数据无法区分的合成数据。TimeGAN (Yoon 等, 2019) 作为一种基于生成对抗网络的架构，被提出用于生成逼真的时间序列数据，其结合了无监督模型的灵活性与有监督模型的可控性。该架构利用嵌入函数和恢复函数从时间序列数据中提取高维特征，随后将这些特征输入序列生成器和序列判别器进行对抗训练。另一项研究提出了一种基于循环神经网络 (RNN) 的生成对抗网络架构，用于生成实值多维时间序列 (Takahashi 等, 2019)。该研究引入了两种变体：递归生成对抗网络 (RGAN) 和递归条件生成对抗网络 (RCGAN)，其中 RGAN 生成实值数据序列，而 RCGAN 则基于特定输入条件生成序列。RGAN 与 RCGAN 的判别器和生成器均基于简单的循环神经网络架构实现。

sequences, and RCGAN generates sequences conditioned on specific inputs. The discriminators and generators of both RGAN and RCGAN are based on simple RNN architectures.

此外，有研究提出了一种基于深度神经网络的方法来建模金融时间序列数据 (Takahashi等, 2019)。该方法通过数据驱动的方式学习数据特性并生成具有真实性的数据，同时保留了金融时间序列的统计特征，包括非线性可预测性、厚尾收益分布、波动率聚集效应、杠杆效应、从粗到细的波动相关性以及非对称收益/损失模式等特征。

Furthermore, a deep neural network-based approach was proposed for modeling financial time series data (Takahashi et al., 2019). This approach learns the properties of the data and generates realistic data in a data-driven manner, while preserving statistical characteristics of financial time series such as nonlinear predictability, heavy-tailed return distributions, volatility clustering, leverage effect, coarse-to-fine volatility correlations, and asymmetric return/loss patterns.



**Fig. 6** The overview of TimeGAN model

这些研究凸显了生成对抗网络在时间序列预测领域的应用，特别是在生成合成时间序列数据及捕捉现实世界时间序列数据特征方面的作用。

These studies highlight the application of GANs in TSF, specifically in generating synthetic time series data and capturing the characteristics of real-world time series data.

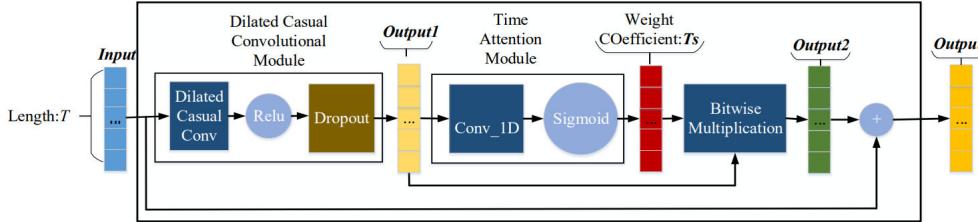
### 3.2 Model without Explicit Structure

#### 3.2.1 Integrated Model

As widely known, recurrent neural networks (RNNs) are often considered suitable for sequence modeling, and the chapter on sequence modeling in classic deep learning textbooks is titled “Sequence Modeling: Recurrent and Recursive Nets” (Heaton, 2018).

众所周知，循环神经网络（RNNs）通常被认为适用于序列建模任务，经典深度学习教材中关于序列建模的章节便以《序列建模：循环与递归网络》为标题 (Heaton, 2018)。时间序列数据天然属于序列建模范畴，因此RNN、LSTM、GRU等模型理应适用于解决时间序列相关任务。然而在音频合成、词级语言建模和机器翻译等领域，卷积架构却取得了最先进的精度表现 (Bai 等, 2018a)，这一现象引发广泛关注，促使研究者探索如何将卷积架构应用于序列建模领域。集成模型由此应运而生。

Time series naturally falls within the realm of sequence modeling tasks, and therefore, RNNs, LSTM, GRU, and similar models are expected to be applicable to solve time series-related tasks. However, convolutional architectures have achieved state-of-the-art accuracy in tasks such as audio synthesis, word-level language modeling, and machine translation (Bai et al., 2018a), which has garnered significant attention and led to inquiries on how to apply convolutional architectures in the domain of sequences. Integrated models have emerged as a solution.



**Fig. 7** The overview of TATCN model

Integrated models can combine the strengths of individual model architectures, with each focusing on learning features it excels at, resulting in improved performance. For example, convolutional architectures excel at learning local feature patterns, while recurrent architectures excel at learning temporal dependencies between nodes. Integrated models have also found various applications in time series tasks (Bai et al., 2018a; Shi et al., 2015; Asiful et al., 2018). In (Shi et al., 2015), precipitation forecasting was modeled as a spatio-temporal sequence prediction problem, where a convolutional architecture was designed to replace fully connected layers in LSTM for sequence modeling, effectively leveraging the advantages of both convolutional and recurrent architectures. Similarly, Asiful et al. (2018) integrated multiple network architectures, namely LSTM and GRU, for stock prediction. In this model, the input was first fed into the LSTM layer, then into the GRU layer, and finally into a dense network.

### 3.2.2 Cascade Model

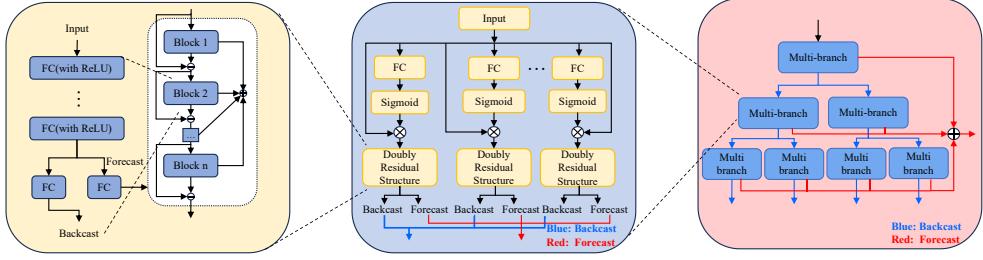
Cascade networks, which are widely used in deep neural networks, especially in Computer Vision (CV) domain (Cai and Vasconcelos, 2018), have multiple applications. A cascade network typically consists of multiple components, each serving a different function, collectively forming a deeper and more powerful network model. The components in a cascade model can be either identical or different. When the components are different, each component has a specific role and function. If the components are the same, it means that a particular module or the entire network is repeated several times. When the same component is repeated multiple times, its concept is somewhat similar to the iterative approach used in solving optimization problems.

In the field of TSF, there are not many works specifically known for their cascade models. However, the concept of cascade is widely applied in various network model architectures. Firstly, stacking multiple identical modules or the entire network can be

集成模型能够融合不同模型架构的优势，使每种架构专注于学习其擅长的特征模式，从而提升整体性能。例如，卷积架构擅长捕捉局部特征模式，而循环架构则擅长学习节点间的时间依赖性。此类集成模型在时间序列任务中已展现出广泛的应用价值(Bai等, 2018a; Shi等, 2015; Asiful等, 2018)。在Shi等(2015)的研究中，降水预测被建模为时空序列预测问题，研究者设计了一种卷积架构替代LSTM中的全连接层进行序建模，有效结合了卷积与循环架构的双重优势。类似地，Asiful等(2018)通过整合LSTM和GRU两种网络架构构建了股票预测模型，该模型先将输入数据传递至LSTM层，再经GRU层处理，最终通过密集网络输出预测结果。

级联网络在深度神经网络中具有广泛应用，尤其在计算机视觉领域(Cai和Vasconcelos, 2018)。这类网络通常由多个组件构成，每个组件承担不同功能，共同形成更深层、更强大的网络模型。级联模型中的组件既可以是同构的也可以是异构的。当组件异构时，每个组件都具有特定的角色和功能；若组件同构，则意味着特定模块或整个网络被多次重复。当相同组件被多次重复时，其概念在某种程度上类似于优化问题求解中采用的迭代方法。

在时间序列预测(TSF)领域，专门以其级联模型设计而闻名的研究工作并不多见。然而，级联的概念在各种网络模型架构中得到了广泛应用。首先，堆叠多个相同模块或整个网络即可视为运用了级联思想，这在Transformer系列模型中有充分体现。此外，一些模型采用了特殊设计的级联方法，旨在确保信息以特定方式流动，从而实现独特的效果。



**Fig. 8** The overview of TreeDRNet model

considered as utilizing the cascade idea, as seen in the Transformer series (Makridakis, 1978; Cleveland et al., 1990; Li et al., 2019a; De Livera et al., 2011). Additionally, some models (Zhou et al., 2022c) incorporate specially designed cascade approaches to ensure the flow of information in a specific manner, thereby achieving unique effects.

## 4 Series Components and Enhanced Feature Extraction Methodology

在前文章节中，我们已系统阐述了构建深度时序特征模型的五大主流范式，为研究者提供了一条理解与构建深度学习paradigms for constructing DTSF models. These paradigms offer researchers a concise pathway to understanding and building DL models. However, a macroscopic understanding与构建深度时序特征模型仍显不足。本章将深入探讨时序特征学习的法论体系，通过预训练、分解、提取与精炼的递进过程，使模型能够更精准地捕捉数据的本质表征，这一过程严格遵循数据的内在特性进行设计

In the previous sections, we have provided a comprehensive overview of five prominent paradigms for constructing DTSF models. These paradigms offer researchers a concise pathway to understanding and building DL models. However, a macroscopic understanding of the deep learning paradigm for time series feature extraction is still lacking. This chapter delves into the methodological aspects of learning temporal features, which enable models to better capture the underlying representations of the data, emphasizing a pre-training, decomposition, extraction, and refinement process that aligns closely with the intrinsic nature of data.

本章分为两部分。首先剖析现实世界中时间序列数据的构成要素，随后深入探讨四种理论基础扎实、领域内表现突出的成熟特征提取方法。这些方法有助于更全面地理解时间序列数据及其核心特征

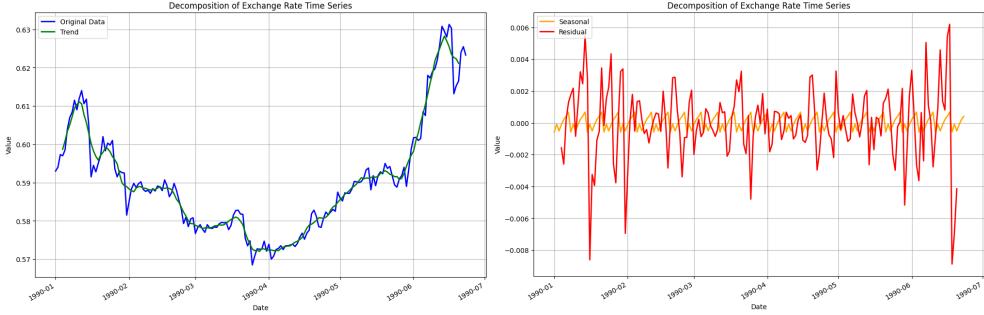
The chapter is divided into two parts. It begins by dissecting the constituents of time series data in the real world. Subsequently, it proceeds to provide an in-depth exploration of four well-established feature extraction methods with strong theoretical foundations and notable performance in the field. These methods facilitate a richer understanding of time series data and its essential features.

### 4.1 Components of a Time Series

In general, time series data can be decomposed into three main components: trend, seasonality, and residuals or white noise (Shumway et al., 2000), as illustrated in Figure 9.

#### 4.1.1 Trend

Represents the long-term changes in the time series data and reflects the overall growth or decline of the data over an extended period (Montgomery et al., 2015). For example, the increase in population over the years exhibits an upward trend (Adhikari and



**Fig. 9** Components of the time series. The data is sourced from the Exchange-Rate dataset spanning from January 1, 1990, to June 23, 1990. The blue line represents the original data, the green indicates the trend, the yellow represents seasonality, and the red signifies the residuals

Agrawal, 2013), and the growing wind power generation during multiple windy seasons can also be considered an upward trend.

#### 4.1.2 Seasonality

Refers to the periodic variations observed in time series data, often caused by seasonal, monthly, weekly, or other time unit influences. For instance, the number of tourists and ice cream sales tend to increase during long vacations or in the summer.

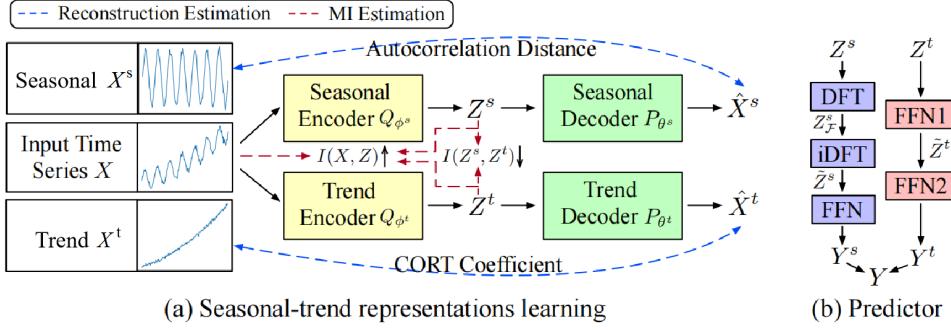
#### 4.1.3 Residuals

Represent the part of the data that cannot be explained by the trend and seasonality components (Maronna et al., 2019). They capture the random fluctuations or noise remaining after the decomposition of trend and seasonality. Residuals reflect the short-term fluctuations and irregularities that have not been modeled in the time series data. Additionally, residuals exhibit some autocorrelation, which can help us identify and adjust for potential flaws in the model, further enhancing the quality and reliability of forecasting.

In the real world, time series data contains discrete information and is non-stationary, meaning that its mean and variance are not constant over time. By decomposing the data into its constituent parts, we gain a better understanding of the data's structure, identify long-term trends and periodic variations, and distinguish them from random noise. These decomposition components aid in making more accurate forecasts, uncovering hidden patterns, extracting useful information, and providing insights into the mechanisms and regularities underlying the time series data.

## 4.2 Methodology for Enhanced Feature Extraction

Numerous studies have been dedicated to improving the model architecture and refining its components in DTSF. These studies aim to enhance the predictive performance



**Fig. 10** The overview of LaST model

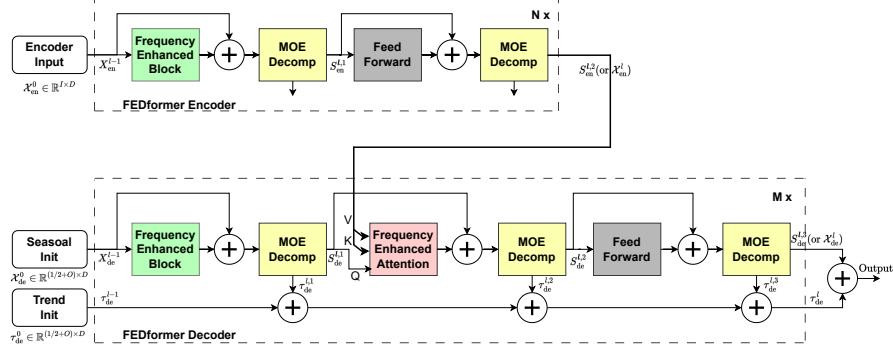
of models by optimizing or replacing the methods used for extraction and feature learning. To achieve accurate predictions, it is crucial to learn time series representation features thoroughly, and sufficient information is essential for training high-quality model parameters.

In recent years, influential works on DTSF have shown significant changes in data processing and component modeling. Notably, decomposing time series into its major components for analysis has been a primary focus, facilitating a more comprehensive exploration of trends and seasonal dimensions. Furthermore, transforming time-domain data into the frequency domain has proven to be more effective in feature differentiation. Additionally, exploring non-end-to-end approaches and devising suitable data pre-training methods to address the potential mismatch between the target task and the data is also a valuable consideration. In the following sections, we will introduce the primary methodologies for enhancing feature extraction and learning in DTSF.

#### 4.2.1 Dimension Decomposition

Dimension decomposition plays a vital role in the realm of TSF. It involves breaking down the data into its constituent dimensions or components, such as trends, seasonal patterns, and residuals.

In current research, some works have integrated encoder-decoder architectures with seasonal-trend decomposition (Wu et al., 2021; Zhou et al., 2022b; Zhang et al., 2022b; Wang et al., 2022; Zhu et al., 2023; Tang and Zhang, 2023; Cao et al., 2023b; Peng et al., 2023). Wu et al. (2021) in the similar work, devised an internal decomposition block to endow deep forecasting model with intrinsic progressive decomposition capability. Subsequently, Zhou et al. (2022b) proposed a seasonal-trend-based frequency enhanced decomposition Transformer architecture in the FEDformer framework. Additionally, Wang et al. (2022) introduced the LaTS model, leveraging variational inference to unravel latent space seasonal trend features, and Zhang et al. (2022b) presented the TDformer model, using MLP to model trends and Fourier attention to simulating seasonality. Notably, Zhu et al. (2023) designed an approach to decompose input sequences into trend and residual components across multiple scales,



**Fig. 11** The overview of FEDformer model

which summed the learned features as the model output. In recent work, the challenge of capturing outer-window variations was overcome by employing contrastive learning and an enhanced decomposition architecture (Park et al., 2024). It is observed that decomposition networks can significantly benefit contrastive loss learning of long-term representations, thereby enhancing the performance of long-term forecasting.

The significance of dimension decomposition lies in its ability to delve into and capture the inherent components or dimensions within time series data. On one hand, it aids in isolating and extracting latent patterns in time series data for identification and analysis. On the other hand, it isolates individual features that influence the overall behavior, allowing for a more focused analysis of each constituent part. This contributes to understanding the impact of each feature on the overall time series. Furthermore, decomposing data dimensions enhances the interpretability of TSF models, which facilitates a better understanding of the influence of different components on overall temporal behavior. As a relatively universal method in time series analysis, dimension decomposition plays a foundational yet crucial role in enhancing feature extraction methodologies.

#### 4.2.2 Time-Frequency Conversion

The time-frequency domain conversion plays a crucial role in deep learning-based time series forecasting tasks. It refers to converting the time-domain data into its frequency-domain representation, enabling a more effective analysis of the frequency, spectral characteristics, and dynamic variations within time series data.

In current research, the time-frequency domain conversion finds extensive application in the preprocessing and feature extraction of time series data (Kourentzes et al., 2014; Chen et al., 2023; Sun and Boning, 2022). This method reveals the components of the data at different frequencies and aids in identifying repetitive patterns, periodic trends, and frequency-domain features such as seasonal patterns or periodic oscillations (Zhou et al., 2022b). Converting time series data into spectrograms provides an overview of the data's distribution in the frequency domain, facilitating the identification of major frequency components and the shape of the spectrum. This is particularly valuable for capturing the overall spectral characteristics of signals and

the primary fluctuation patterns across frequencies. In their work, (Cao et al., 2020) employ StemGNN to jointly capture inter-sequence correlations and temporal dependencies in the spectral domain for multivariate time series forecasting. In recent work, Yi et al. (2023) proposed a simple yet effective time series forecasting architecture, named FreTS, based on Frequency-Domain MLP. It primarily consists of two stages, domain conversion and frequency learning, which enhance the learning of channel and temporal correlations across both inter-series and intra-series scales.

Furthermore, employing time-frequency domain conversion can help reduce the impact of noise and interference (Zhou et al., 2022a; Gu et al., 2021). In specific time series forecasting scenarios, noise may affect the data, resulting in a decline in the model's predictive performance. In the FiLM model, Zhou et al. (2022a) introduced a Frequency Enhancement Layer to address this issue. They achieved noise reduction by combining Fourier analysis and low-rank matrix approximation, which minimized the influence of noise signals and mitigated overfitting problems. Apparently, converting time-domain data into the frequency-domain, along with operations like filtering and denoising in the frequency domain, proves effective in lessening the impact of noise.

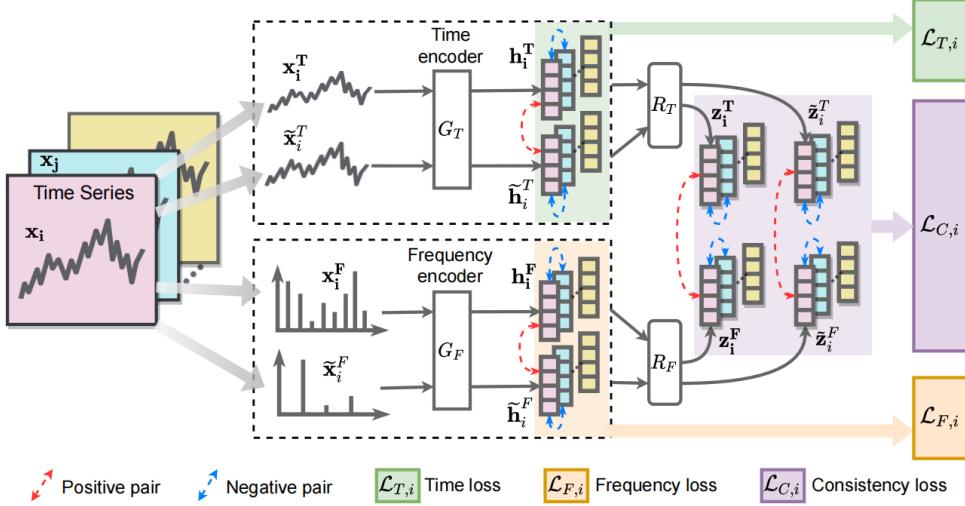
The importance of time-frequency domain conversion lies in providing a comprehensive and detailed approach to data analysis, which is capable of unveiling the hidden frequency characteristics and dynamic changes within time series. This technique has been widely employed in the domain of TSF, representing a crucial methodology for enhancing predictive performance and comprehending the intricacies of time series data.

#### 4.2.3 Pre-training

Compared to natural language, temporal data exhibits lower information density, necessitating longer sequences to capture temporal patterns. Additionally, temporal data also exist challenges such as temporal dynamics, rapid evolution, and the presence of both long and short-term effects. Due to potential mismatches between pre-training and target domains, downstream performance might suffer. Recent endeavors in TSF involve novel attempts at self-supervised and unsupervised pre-training, yielding promising results (Rebjock et al., 2021; Sun et al., 2021; Sarkar and Etemad, 2020; Cheng et al., 2020). In certain scenarios, the adoption of sampling pre-training methods could be considered.

**Contrastive pre-training.** Due to potential mismatches between pre-training and the target domain, there is a unique challenge in time series pre-training that may lead to diminished downstream performance. While domain adaptation methods can alleviate these changes (Berthelot et al., 2022; Singh, 2021), most approaches are considered suboptimal for pre-training as they often require direct examples from the target domain. To address this, these methods need to adapt to the diverse temporal dynamics of the target domain without relying on any target examples during pre-training.

Contrastive learning, a form of self-supervised learning, aims to train an input encoder to map positive sample pairs closer and negative pairs apart (Oord et al., 2018). In time series, if the representations based on time and frequency for the same



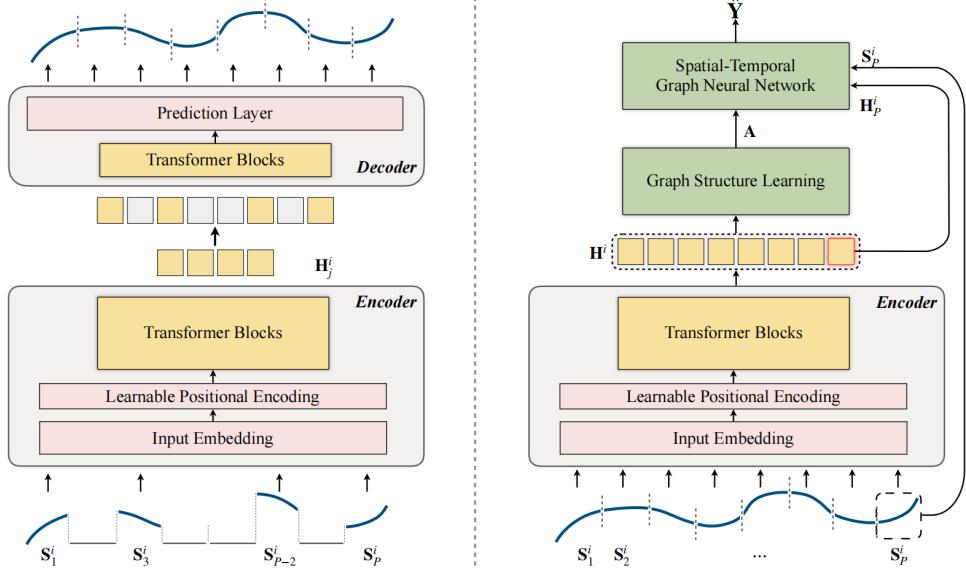
**Fig. 12** The overview of TF-C

instance are close in the time-frequency space, it suggests a certain similarity or consistency in their features or attributes. Zhang et al. (2022a) proposed the need for Time-Frequency Consistency (TF-C) in pre-training, which involves embedding the time-based neighborhood of an example close to its frequency-based neighborhood. This work employs frequency-based contrastive enhancement to leverage rich spectral information and explore time-frequency consistency in time series. Contrastive pre-training can provide robust feature representations for forecasting tasks, contributing to enhanced model performance and generalization.

**Masking Pre-training.** Time series data is often continuous, ordered, but practically exhibits incompleteness. Additionally, real-world time series data commonly contains noise and uncertainty, necessitating models to possess robustness in dealing with such uncertainties. To address these crucial challenges in practice, the masking mechanism is regarded in some studies as an effective approach to enhance feature extraction.

In the work STEP, Shao et al. (2022) designed an unsupervised pre-training model for time series based on Transformer blocks. The model employs a masked autoencoding strategy for training, which effectively learns temporal patterns and generates segment-level representations. These representations provide contextual information for subsequent inputs, facilitating the modeling of dependencies between short-term time series. The Ti-MAE model (Li et al., 2023b) exhibits analogous efficacy in this regard. In the pre-training model SimMTM, Dong et al. (2023) highlighted that randomly masking parts of the data severely disrupts temporal variations. They relate masking modeling to manifold learning and propose a Simple pre-training framework for Masked Time-series Modeling.

In summary, Masking pre-training simulates incompleteness and noise by masking some data points, enabling the model to learn how to handle partially missing information during the pretraining phase. This methodology can enhance the model's



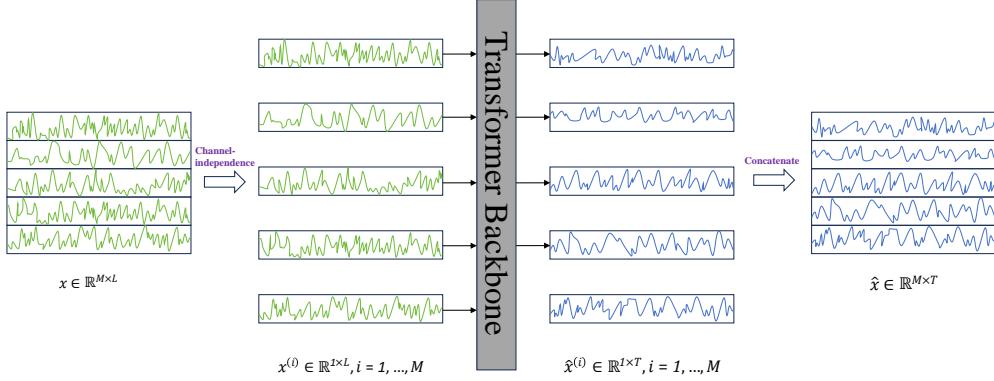
**Fig. 13** The overview of STEP

ability to capture long-term dependencies, increase tolerance to data uncertainty, and improve overall generalization performance.

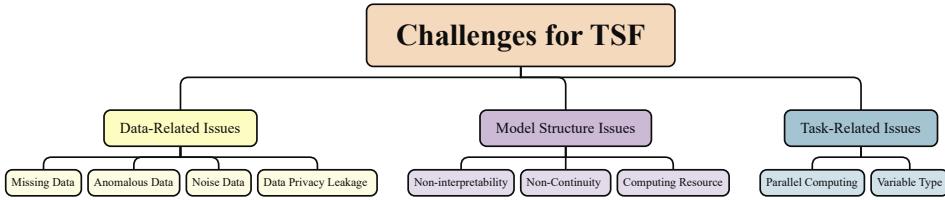
#### 4.2.4 Patch-based segmentation

In recent DTSF works, especially those of the Transformer models, the adoption of patch-based data organization has become prevalent (Nie et al., 2022; Lin et al., 2023; Zhang et al., 2023b; Ekambaram et al., 2023; Xue et al., 2023; Gong et al., 2023). It is advantageous to enhance the model's local perception capabilities by employing a patch-based strategy. Through segmenting long time series into smaller patches, the model becomes more adept at capturing short-term and local patterns within the sequence, thereby augmenting its comprehension of complex dynamics in the sequence. Simultaneously, the relationships among multivariate variables can yield information gain. Challenges lie primarily in how to learn the relationships among individual variables and introduce valid information into the model, while avoiding redundant information that may interfere with the model training process.

Nie et al. (2022) proposed the PatchTST model, where they segment time series into subseries-level patches, serving as input tokens for the Transformer. They independently model each channel to represent a single variable. This channel-independent approach not only effectively preserves local semantic information for each variable in the embedding but also focuses on a more extended history. Furthermore, leveraging the channel-independent characteristics, potential feature correlations between single variables can be further learned through graph modeling methods (Zhang et al., 2023c). It allows for spatial aggregation of representations for global tokens in the graph.



**Fig. 14** The overview of PatchTST



**Fig. 15** Challenges in Time Series Forecasting

While the modeling emphasis varies across different works, there is a common consideration of employing methods that utilize subseries-level patches to process the raw time series data. This approach proves highly beneficial for capturing and learning the local features of the data. The patch-based segmentation method introduces another methodology for TSF. Additionally, channel independence emerges as a viable avenue for exploring multivariate time series forecasting.

## 5 Challenges and Prospects

We have investigated the neural network architectures, feature extraction and learning approaches, and significant experimental datasets of deep learning models in the context of TSF. While DTSF models have demonstrated remarkable achievements across diverse domains in recent years, certain challenging issues remain to be addressed, which point towards potential future research directions. We summarize these challenges and propose viable avenues as follows. We classify the challenges into three main categories: data features, model structure, and task-related issues. Within each category, we highlight several representative challenges. Figure 15 illustrates an overview of these challenges.

**Table 3** Time Series Datasets in Primary Domains. The table summarizes commonly used datasets and indicates whether they are multivariate, which implies temporal alignment with known timestamps

Domain	Datasets	Variants	Data Time Range	Data Granularity	Multi/Uni	Authors
Energy	<a href="#">ETTh1</a>	7	2016 - 2018	1h	Multi+Uni	Zhou et al.
	<a href="#">ETTm1</a>	7	2016 - 2018	15m	Multi+Uni	Zhou et al.
	<a href="#">Electricity</a>	321	2011 - 2014	1h	Multi+Uni	-
	<a href="#">Wind</a>	28	1986 - 2015	1h	Uni	-
	<a href="#">Solar-Energy</a>	137	2006 - 2006	10m	Multi+Uni	Solar
Healthcare	<a href="#">ILI</a>	7	2002 - 2021	1w	Uni	-
	<a href="#">MIT-BIH</a>	2	1975 - 1979	360Hz	Uni	George
Transportation	<a href="#">Traffic</a>	862	2015 - 2016	1h	Uni	Caltrans
	<a href="#">PeMSD4</a>	307	2018/1	5m	Multi	Chen et al.
	<a href="#">PeMSD7</a>	228	2012/5			
	<a href="#">PeMSD8</a>	170	2016/7			
Meteorology	<a href="#">Weather1</a>	12	1981 - 2010	1h	Uni	-
	<a href="#">Weather2</a>	21	2020 - 2021	10m	Multi+Uni	Sparks et al.
	<a href="#">Temperature</a>	2	2015 - 2017	1d	Multi+Uni	Rakshitha et al.
Economics	<a href="#">Exchange-Rate</a>	8	1990 - 2016	1d	Uni	Lai et al.
	<a href="#">LOB-ITCH</a>	149	2010 - 2010	1ms-10min	Uni	Adamantios et al.
	<a href="#">Dominick</a>	25	1989 - 1994	1w	Uni	Godahewa et al.

## 5.1 Challenges

### 5.1.1 Lack of Data Privacy Protection and Completeness

Federated learning (FL) is gaining momentum in the field of TSF, primarily addressing challenges associated with large local data volumes and privacy concerns during information exchange. With FL, multiple participants can collaboratively train models without the need to share sensitive raw data (McMahan et al., 2017). In TSF tasks, each participant can leverage their local time series data for model training. Through FL algorithms, the parameters of local models are aggregated to obtain a global predictive model. This distributed learning process ensures privacy protection, mitigating the risks of privacy breaches associated with centralized data storage and transmission. Current research efforts predominantly focus on load detection (Gao et al., 2021; Taïk and Cherkaoui, 2020; Briggs et al., 2022), traffic speed and flow (Zhang et al., 2021; Liu et al., 2020), energy consumption (Zhang et al., 2020; Savi and Olivadese, 2021), and communication networks (Subramanya and Riggio, 2021; Díaz González, 2019), among others. Exploring feasible solutions in other domains remains an open

avenue. Furthermore, federated learning harnesses the diversity of distributed data sources, thereby enhancing model generalization and prediction accuracy. Hence, federated learning holds great promise in the realm of TSF, offering a prospective solution for large-scale, secure, and efficient time series prediction and analysis.

### 5.1.2 Lack of Interpretability

So far, the majority of efforts in the field of TSF have primarily focused on enhancing predictive performance through the design of intricate model architectures. However, research into the interpretability of these models has been relatively limited. As neural networks find application in critical tasks ([Moraffah et al., 2020](#)), the demand for comprehending why and how models make specific predictions has been growing. The N-BEATS model achieves high accuracy and interpretability in TSF by designing the interpretable architecture and output mechanisms ([Oreshkin et al., 2019](#)). This enables users to better comprehend the model's predictive outcomes while maintaining high forecasting precision.

Post-hoc interpretable models are developed for the purpose of elucidating already trained networks, aiding in the identification of crucial features or instances without modifying the original model weights. These approaches mainly fall into two categories. One involves the application of simpler interpretable surrogate models between the inputs and outputs of the neural network, relying on these approximate models to provide explanations ([Ribeiro et al., 2016](#); [Lundberg and Lee, 2017](#)). The other category encompasses gradient-based methods, such as those presented in ([Simonyan et al., 2013](#); [Koh and Liang, 2017](#); [Siddiqui et al., 2019](#)), which scrutinize the network gradients to determine which input features exert the most significant influence on the loss function.

Furthermore, it is noteworthy that, in contrast to the black-box nature of traditional neural networks, a series of TSF models based on the Transformer architecture incorporate attention layers with inherent interpretability. These attention layers can be strategically integrated into other models, with the analysis of attention weights aiding in the comprehension of the relative importance of features at each time step ([Choi et al., 2016](#); [Li et al., 2019a](#); [Bai et al., 2018b](#)). By scrutinizing the distribution of attention vectors across time intervals, the model can gain better insights into persistent patterns or relationships within the time series ([Lim et al., 2021](#)), such as seasonal patterns.

Recent advancements in the field have focused on learning from perturbations and interpretable sparse system identification methods to enhance the interpretability of time series data ([Enguehard, 2023](#); [Liu et al., 2024](#)). Among these, sparse optimization methods, which obviate the need for time-consuming backpropagation training, exhibit efficient training capabilities on CPUs. These methods offer insights for further exploration into interpretable time series forecasting.

### 5.1.3 Lack of Temporal Continuity

Compared to traditional deep learning forecasting models, the proposal of the Neural Ordinary Differential Equation (NODE) ([Chen et al., 2018](#)) has directed our attention

towards the derivatives of neural network parameterized hidden states, which showcases superior performance over RNNs in both continuous and discrete time series problems. Recent studies applying Ordinary Differential Equations (ODE) or Partial Differential Equations (PDE) to TSF have explored various directions such as learning latent relationships between variables or events (Li et al., 2022a; De Brouwer et al., 2019; Gao et al., 2022b), handling irregular data (Scholz et al., 2022), achieving interpretable continuity (Gao et al., 2022a; Jin et al., 2022), optimizing model parameters (Chen et al., 2011), and exploring differential dynamics (Linot et al., 2023; Gilani, 2021). The ETN-ODE model proposed by Gao et al. (2022a) is the first interpretable continuous neural network for multi-step time series forecasting of multiple variables at arbitrary time instances. Additionally, their EgPDE-Net model (Gao et al., 2022b) is also the first to establish the continuous-time representation of multivariate time series as a partial differential equation problem. Its specially designed architecture utilizes ODE solvers to transform the partial differential equation problem into an ODE problem, facilitating predictions at arbitrary time steps.

Temporal continuation is one of the crucial factors to consider in the TSF process. The application of the Neural Differential Equation (NDE) paradigm in DTSF integrates DL with differential equation modeling to naturally and accurately capture the dynamic evolution of time series. It interprets the evolution of individual components more clearly and flexibly captures instantaneous changes by using a differential equation to describe the rate of change of the data at each time point. For deep learning modelling of complicated time series data, the NDE technique offers an innovative and effective paradigm.

#### 5.1.4 Challenges of Parallel Computing

In the era of massive data, there is an urgent demand for online real-time analysis of time series data. Currently, time series models are constructed based on stand-alone sequence analysis, which often requires the use of high-performance GPU servers to improve computational efficiency. However, on one hand, it is constrained by computational resources and data scale, making real-time online forecasting unattainable. On the other hand, GPU servers are costly. Therefore, the research on efficient parallel computing based on deep learning and big data analytics technologies is poised to become a critical challenge.

#### 5.1.5 Challenges of Large Models

Large models demonstrate advantages in the field of time series forecasting, excelling in capturing long-term dependencies, handling high-dimensional data, and mitigating noise. A noteworthy exploration in this direction occurred on December 13, 2023 when Amazon released work utilizing large models for time series forecasting, marking a pioneering effort in applying large models to temporal prediction (Xue and Salim, 2023). This work leverages large models to construct intricate relationships between sequences while harnessing their robust text data processing capabilities. The integration of large models has enhanced the handling of multimodal data and interpretability in financial forecasting scenarios. Large models have already ventured into various domains, encompassing stock price predictions in financial markets (Zhou et al., 2023;

Jin et al., 2023; Chang et al., 2023), inference of medical data (Sun et al., 2023; Gruver et al., 2023), forecasting human mobility trajectories (Cao et al., 2023a), and serving as general-purpose models for weather and energy demand predictions (Yu et al., 2023; Xie et al., 2023; Zhang et al., 2023a; Liu et al., 2023b; Li et al., 2023a).

On another note, significant strides have been made in the training of foundational time series models (Xue et al., 2022; Garza and Mergenthaler-Canseco, 2023). The recent TimeGPT-1 model (Rasul et al., 2023) applies the techniques and architecture underlying large language models (LLM) to the forecasting domain, successfully establishing the first foundational time series model capable of zero-shot inference. This breakthrough opens avenues for creating foundational models specifically tailored for time series forecasting.

We believe that the performance and value of large models in the realm of time series forecasting will continue to unfold as technological advancements and innovations progress.

## 5.2 Prospects

### 5.2.1 Potential Representation Learning

Representation Learning (RL) has recently emerged as one of the hot topics in time series forecasting. While models based on stacked layers can yield respectable results, they often come with high computational costs and may struggle to capture the inherent features of the data. RL, on the other hand, focuses on acquiring meaningful latent features that result in lower-dimensional and compact data representations, capturing the fundamental characteristics of the data. Presently, many self-supervised or unsupervised approaches aim to encode raw sequences to learn these latent representation features (Eldele et al., 2023; Darban et al., 2023). Some works employ multi-module architectures or model ensembles (Mehrkanooon, 2019; Lyu et al., 2018; Yang and Chen, 2019), while others use pre-training with denoising, smoothing properties, siamese structures or 2D-variation modeling (Zheng et al., 2023; Zerveas et al., 2021; Wu et al., 2022), which provide novel solutions to various domain-specific problems. Besides, contrastive learning is dedicated to enabling models to compare observations at different time points and learn rich data representations by contrasting positive and negative samples. Some works (Yue et al., 2022; Zhang et al., 2022a; Ozyurt et al., 2022; Luo et al., 2023) have utilized contrastive learning to assist models in learning meaningful features from unlabeled data, thus enhancing their generalization performance. This is especially valuable when labeled data is limited or unavailable.

Learning temporal representations and employing contrastive training can significantly enhance the model's representation and generalization capabilities in TSF. This greatly improves the model's performance in handling complex, noisy, or changing data distributions.

### 5.2.2 Counterfactual Forecast and Causal Inference

Counterfactual forecasting and causal inference represent promising avenues for future research in DTSF. Despite the existence of lots of deep learning methods for estimating causal effects in static settings (Yoon et al., 2018; Hartford et al., 2017; Alaa et al.,

2017), the primary challenge in time series data lies in the presence of time-dependent confounding effects. This challenge arises due to the time-dependence, where actions that influence the target are also conditioned on observations of the target. Recent research advancements encompass the utilization of statistical techniques, novel loss functions, extensions of existing methods, and appropriate inference algorithms (Lim, 2018; Bica et al., 2020; Li et al., 2020; Liu et al., 2023a; Gao et al., 2023).

Moreover, while some efforts provide counterfactual explanations for time series models (Dhaou et al., 2021; Nemirovsky et al., 2022), they fall short of generating realistic counterfactual explanations or feasible counterfactual explanations for time series models. Recent work has introduced a self-interpretable model capable of generating actionable counterfactual explanations for time series forecasting (Yan and Wang, 2023).

Future research directions may revolve around further refining these approaches to address the additional complexities inherent in time series data and get more accurate counterfactual interpretations. Additionally, innovative methods should be sought to harness the full potential of deep learning in counterfactual forecasting and causal inference, ultimately enhancing decision-making processes across various domains.

### 5.2.3 TS Diffusion

The burgeoning development of Diffusion models in the domain of image and video streams has sparked novel theories and models, gradually extending into the realm of TSF. Notably, TimeGrad employs RNN-guided denoising for autoregressive predictions (Rasul et al., 2021), while CSDI utilizes non-autoregressive methods with self-supervised masking (Tashiro et al., 2021). Similarly, SSSD utilizes structured state-space models to reduce computational complexity (Alcaraz and Strodthoff, 2022). Despite being early explorations in the TSF domain, these models still suffer from slow inference, high complexity, and boundary inconsistencies.

In recent researches, the unconditionally trained TSDiff model employs self-guidance mechanisms to alleviate the computational overhead in reverse diffusion for downstream task forecasting without auxiliary networks (Kollovieh et al., 2023). TimeDiff addresses boundary inconsistencies with future mixups and autoregressive initialization mechanisms (Shen and Kwok, 2023). The multi-scale diffusion model MR-Diff leverages multi-resolution temporal structures for sequential trend extraction and non-autoregressive denoising (Shen et al., 2024).

The first framework based on DDPM, Diffusion-TS, accurately reconstructs samples using Fourier-based loss functions, extending to forecasting tasks (Yuan and Qiao, 2024). Furthermore, the TMDM model combines conditional diffusion generation processes with Transformer to achieve precise distribution prediction for multivariate time series (Li et al., 2024b).

The work on Diffusion primarily focuses on denoising, and numerous groundbreaking initiatives are emerging in the realm of DTSF. We anticipate Diffusion to become a prominent direction.

#### 5.2.4 Determine the Weight of the Aggregate Model

At present, ensemble learning, as one of the mainstream paradigms, has proven to be effective and robust (Taylor et al., 2009; Makridakis et al., 2018b; Arbib, 2003). However, determining the weights of base models in an ensemble remains an unsolved challenge. Sub-optimal weighting can hinder the full potential of the final model. To address this challenge, Fu et al. (2022b) proposed a model combination framework based on reinforcement learning (RLMC). It uses deterministic policies to output dynamic model weights for non-stationary time series data and leverages deep learning to extract hidden features from raw time series data, allowing rapid adaptation to evolving data distributions. Notably, in RLMC, the use of DDPG, an off-policy actor-critic algorithm (Lillicrap et al., 2015), can produce continuous actions suitable for model combination problems and is trained with recorded data to achieve improved sample efficiency. Therefore, the combination of reinforcement learning with some continuous control algorithms (Fujimoto et al., 2018; Haarnoja et al., 2018) presents a unique utility in determining ensemble model weights and is a path worth exploring.

#### 5.2.5 Interdisciplinary Exploration

Due to the multidimensional nature of the relationships between causes and effects in reality, there exist complex interconnections among time series. While deep learning models have demonstrated excellent performance in tackling intricate TSF problems, they often lack systematic interpretability and clear hierarchical structures. In the realm of network science, when dealing with extensive data, numerous variables, and intricate interconnections, it is possible to construct multi-layered networks by categorizing and stratifying the relationships among various elements. By examining the dynamic changes in multi-layered networks, it becomes feasible to forecast multidimensional data by analyzing high-dimensional correlations.

For diverse domains, an interdisciplinary approach, such as incorporating network science or other relevant theories, can be a beneficial choice in the future of DTSF research. This approach enables a more insightful analysis of problems and their multidimensional aspects.

## 6 Conclusion

In this paper, we present a systematic survey for deep learning-based time series forecasting. We commence with the fundamental definition of time series and forecasting tasks and summarize the statistical methods and their shortcomings. Next, moving on, we delve into neural network architectures for time series forecasting, summarizing five major model paradigms that have gained prominence in recent years: the Encoder-Decoder, Transformer, Generative Adversarial, Integration, and Cascade. Furthermore, we conduct an in-depth analysis of time series composition, elucidating the primary approaches to enhance feature extraction and learning from time series data. Additionally, we survey time series forecasting datasets across major domains, encompassing energy, healthcare, traffic, meteorology, and economics. Finally, we comprehensively outline the current challenges in the field and propose some potential research directions.

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## A Datasets in Different Domain

Time series, which exists in every aspect of our lives, carries the historical data of various fields in the time dimension. Many datasets have been accumulated during the development of the TSF task. These datasets are often cited in top conferences and journals within the computer domain, furnishing researchers with high-quality research data characterized by rich samples and features, thus holding significant reference value. However, the diversity of these datasets introduces a significant challenge—data heterogeneity. The datasets described below cover five key TSF application areas: energy, transportation, economics, meteorology, and healthcare (Gebodh et al., 2021), as shown in Table 3. These fields feature data with varying structures, formats, time granularities, and scales, such as sensor data, text, and images, complicating model construction. To address these issues, several techniques have been proposed.

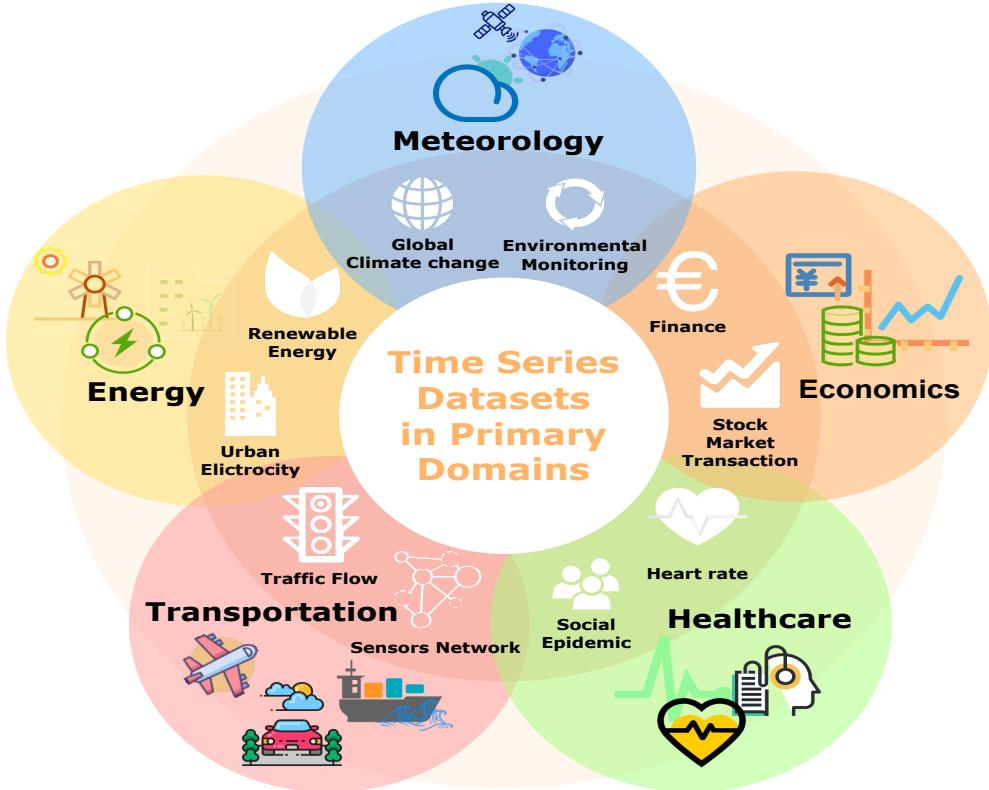
Multimodal learning, through shared representation learning, integrates diverse data types, improving model handling of heterogeneous data (Guo et al., 2019). Time alignment techniques, such as the TAM model, synchronize data from different time granularities by introducing a novel time-distance measure (Folgado et al., 2018). Deep generative models, like GinAR, address missing values and noise by generating new samples and rebuilding spatiotemporal dependencies (Yu et al., 2024). Self-supervised learning methods, such as SimCLR, allow models to learn from unlabeled data, improving adaptability to heterogeneous sources (Chen et al., 2020a). Finally, collaborative attention mechanisms capture complex correlations between multimodal data and adjust modality weights dynamically, enhancing model learning capacity (Dosovitskiy et al.). These models and techniques effectively integrate heterogeneous data, improving the stability and accuracy of time series forecasting in multi-source environments.

### A.1 Energy

TSF is currently being extensively applied in a prominent domain, namely, energy management. Accurate forecasting within this domain plays a crucial role in facilitating status assessment and trend analysis, which in turn enables the implementation of intelligent strategies in engineering planning. Fortunately, modern energy systems autonomously gather extensive datasets encompassing diverse energy sources such as electricity (Singh and Yassine, 2018), wind energy (Feng et al., 2017), and solar energy (Rajagukguk et al., 2020). These data resources are leveraged for the identification of patterns and trends in energy demand and supply, providing valuable insights for the development of advanced forecasting models.

#### A.1.1 Electricity Transformer Temperature (ETT)

The ETT-small dataset encompasses data originating from two distinct power transformer installations, each situated at a separate site (Zhou et al., 2021). This dataset comprises a variety of parameters, such as load profiles and oil temperature readings. It serves the purpose of predicting the oil temperature of power transformers and investigating their resilience under extreme load conditions. The temporal scope of this dataset spans from July 2016 to July 2018, with data recorded at 15-minute



**Fig. 16** Time series datasets in primary domains

intervals. These datasets originate from two geographically disparate regions within the same province in China, designated as ETT-small-m1 and ETT-small-m2, respectively. Each of these datasets consists of an extensive 70,080 data points, calculated based on a duration of 2 years, 365 days per year, 24 hours per day, and data sampling at 15-minute intervals. Furthermore, the dataset offers an alternate version with hourly granularity, denoted as ETT-small-h1 and ETT-small-h2. Each data point within the ETT dataset is characterized by an 8-dimensional feature vector, which includes the timestamp of the data point, the target variable 'oil temperature', and six distinct types of external load values.

### A.1.2 Electricity

The initial dataset utilized in this investigation is the Electricity Load Diagrams 2011-2014 Dataset ([Trindade, 2015](#)), which records 370 customers' electricity usage information between 2011 and 2014. Data is recorded in the original dataset every 15 minutes. It was necessary to preprocess the dataset by deleting the 2011 data and

aggregating it into hourly consumption in order to address the problem of some dimensions having a value of 0. As a result, the final dataset includes information on 321 customers' electrical use from 2012 to 2014.

#### A.1.3 Wind (European Wind Generation)

For 28 European countries between 1986 and 2015, this dataset <sup>1</sup> offers hourly estimates of energy potential expressed as a percentage of the maximum output from power plants. It is distinguished from other datasets by having sparser data and a notable frequency of zeros at regular intervals.

#### A.1.4 Solar-Energy

The solar power production of 137 photovoltaic plants in Alabama State in 2006, recorded at 10-minute intervals, constitutes the dataset for our evaluation of short-sequence forecasting capabilities <sup>2</sup>.

### A.2 Healthcare

TSF plays a pivotal role in the healthcare domain, serving as a critical tool for predicting disease onset and progression, evaluating the efficacy of pharmaceutical interventions, and monitoring fluctuations in patients' vital signs. These forecasts empower healthcare practitioners in enhancing disease diagnosis, devising treatment strategies, overseeing patient well-being, and implementing preventive measures for disease surveillance and containment.

#### A.2.1 ILI (Influenza-Like Illness)

Weekly reports from the US Centers for Disease Control and Prevention from 2002 to 2021 are included in the set of data. It contains data on the overall number of patients as well as the percentage of patients having influenza-like symptoms.

#### A.2.2 EEG (Electroencephalogram)

The collection includes EEG <sup>3</sup> recordings of participants obtained both prior to and during the performance of mental math exercises. Every recording is made up of 60-second EEG segments free of artifacts. For every subject in the dataset, there are 36 CSV files total, and each file has 19 data channels.

#### A.2.3 MIT-BIH (Arrhythmia Database)

There are 48 half-hour segments of two-channel ambulatory ECG recordings available in the MIT-BIH Arrhythmia Database <sup>4</sup>. These recordings were from 47 individuals that the BIH Arrhythmia Laboratory examined from 1975 to 1979. Every recording was digitalized with a resolution of 11 bits and a range of 10 mV, at a rate of 360

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<sup>1</sup><https://www.kaggle.com/datasets/sohier/30-years-of-european-wind-generation>

<sup>2</sup><https://www.nrel.gov/grid/solar-power-data.html>

<sup>3</sup><https://github.com/meagmohit/EEG-Datasets>

<sup>4</sup><http://ecg.mit.edu/>

samples per second per channel. Electrocardiogram data from this dataset can be used for anticipating arrhythmias, among other uses.

### A.3 Transportation

Accurate and timely TSF of traffic is vital for urban traffic control and management. It aids in predicting traffic congestion, traffic flow, accident rates, and the utilization of public transportation. These predictions can be used by transportation authorities and companies to plan and manage transportation systems more effectively, thereby improving traffic efficiency and safety.

#### A.3.1 Traffic

This dataset <sup>5</sup> includes hourly data from 2015–2016 that was collected during a 48-month period from the California Department of Transportation. The statistic shows the hourly road occupancy rate, which ranges from 0 to 1. The San Francisco Bay Area's roadways are home to 862 different sensors from which the measurements are obtained.

#### A.3.2 PeMSD4/7/8

These datasets are highly regarded as industry standards for traffic forecasting ([Chen et al., 2001](#)).

PeMSD4 is one of them and it includes traffic speed data from the San Francisco Bay Area. It incorporates data from 29 roads' worth of 307 sensors. The January–February 2018 time frame is covered by the dataset.

PeMSD7 includes traffic information from California's District 7. It covers the workday period from May to June 2012 and includes traffic speeds recorded by 228 sensors. Five minutes are allotted for the collection of data.

PeMSD8 contains San Bernardino traffic statistics taken during July and August of 2016. It includes data from 170 detectors positioned along 8 distinct routes. Five minutes are allotted for the collection of data.

### A.4 Meteorology

TSF has become an indispensable task in the field of meteorology with wide-ranging applications in weather forecasting, such as meteorological disaster warnings, agricultural production, and more.

#### A.4.1 Weather1

The dataset Weather1 encompasses climate data from almost 1600 locations in the United States <sup>6</sup>, spanning a 4-year period from 2010 to 2013. Hourly data points were collected, featuring the target value "wet bulb" and 11 climate-related features.

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<sup>5</sup><https://pems.dot.ca.gov/>

<sup>6</sup><https://www.ncei.noaa.gov/data/local-climatological-data/>

#### A.4.2 Weather2

Weather2 comprises a meteorological time series featuring 21 weather indicators <sup>7</sup>, collected every 10 minutes in 2020 by the Max Planck Institute for Biogeochemistry's weather station.

#### A.4.3 Temperature Rain

Consisting of 32,072 daily time series, this dataset ([Godahewa et al., 2021a](#)) presents temperature observations and rain forecasts collected by the Australian Bureau of Meteorology. The data spans 422 weather stations across Australia, covering the period from 02/05/2015 to 26/04/2017.

### A.5 Economics

In the field of finance, one of the most extensively studied areas in TSF is the prediction of financial time series, particularly asset prices. Typically, there are several subtopics in this field, including stock price prediction, index prediction, foreign exchange price prediction, commodity (such as oil, gold, etc.) price prediction, bond price prediction, volatility prediction, and cryptocurrency price prediction. The following section will introduce commonly used datasets in this domain.

#### A.5.1 Exchange-Rate

This dataset ([Lai et al., 2018](#)) compiles daily exchange rates mainly in trading days for eight countries (Australia, Canada, China, Japan, New Zealand, Singapore, Switzerland, and the United Kingdom) spanning the years 1990 to 2016.

#### A.5.2 LOB-ITCH

Due to the lack of adequate records, few other fields have Millisecond data on the span of days as in finance. In the financial field, with the advent of automated trading, limit order books were born, which are very conducive to high-frequency traders' operations and leave a large amount of detailed data. The LOB-ITC dataset comprises around four million events, each with a 144-dimensional representation, pertaining over five stocks for ten consecutive trading days ([Ntakaris et al., 2018](#)), from June 1, 2010 to June 14, 2010. And what makes this data different from other data of the same kind is the centralized trading market in the Nordic region. Some researchers found that "the differences between different trading platforms' matching rules and transaction costs complicate comparisons between different limit order books for the same asset ([O'Hara and Ye, 2011](#))". Therefore, Stock Exchange, which has decentralized exchanges like the United States, has more influencing factors and is more difficult to model. In contrast, Helsinki Exchange is a pure limit order market, which can provide purer data.

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<sup>7</sup><https://www.bgc-jena.mpg.de/wetter/>

### A.5.3 Dominick

This dataset ([Godahewa et al., 2021b](#)) incorporates data from randomized experiments conducted by the University of Chicago Booth School of Business and the now-defunct Dominick's Finer Foods. The experiments spanned from 1989 to 1994, covering over 25 different categories across all 100 stores in the chain. As a result of this research collaboration, approximately nine years of store-level data on the sales of more than 3,500 UPCs are available through this resource.

## A.6 Further Data Sources

In addition to the commonly used datasets mentioned above, we extensively surveyed data sources from various domains and compiled a subset of additional datasets. These datasets are derived from influential works and serve as the foundation for researching niche topics and detailed investigations in respective fields. We will provide appropriate descriptions of the datasets listed in Table 4.

Several comprehensive datasets from large-scale competitions are also noteworthy, such as M3/M4/M5. These datasets were put forward by the Makridakis Competitions, which are a series of open competitions to evaluate and compare the accuracy of different TSF methods.

### A.6.1 M3

This dataset <sup>8</sup> comprises yearly, quarterly, monthly, daily, and other time series. To ensure the development of accurate forecasting models, minimum observation thresholds were established: 14 for yearly series, 16 for quarterly series, 48 for monthly series, and 60 for other series. Time series within the domains of micro, industry, macro, finance, demographic, and others were included.

### A.6.2 M4

The M4 dataset ([Makridakis et al., 2018a](#)) encompasses 100,000 real-life series in diverse domains, including micro, industry, macro, finance, demographic, and others.

### A.6.3 M5

Covering stores in three US States (California, Texas, and Wisconsin), this dataset <sup>9</sup> includes item-level, department, product categories, and store details. It incorporates explanatory variables such as price, promotions, day of the week, and special events. Alongside time series data, it incorporates additional explanatory variables (e.g., Super Bowl, Valentine's Day, and Orthodox Easter) influencing sales, enhancing forecasting accuracy.

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<sup>8</sup><https://forecasters.org/resources/time-series-data/>

<sup>9</sup><https://mofc.unic.ac.cy/m5-competition/>

**Table 4** Summary of the datasets used in the experiments

Domain	Variants	Dataset	Data Time Range	Data Granularity	Reference
Energy	21	the Scada wind farm in Turkey	2018/1/1-2018/12/29	10m	(Lin et al., 2021)
	-	Global horizontal solar radiation data	1998/1/1-2007/12/1	1h	(Sorkun et al., 2017)
	-	Rooftop PV plant	2015/1/1-2016/12/31	30m	(Torres et al., 2019)
	9	UCI household electric power consumption	2006/12-2010/11	1m	(Bu and Cho, 2020)
	-	Spanish electricity demand	2014/01/02-2019/11/01	10m	(Lara-Benítez et al., 2020)
	-	Electric Vehicles Power Consumption	2015/3/2-2016/5/31	1h	(Lara-Benítez et al., 2020)
Healthcare	-	CDC ILI data	2010-2018	1d	(Wu et al., 2020a)
	45	DEAP	-	1 interval	(Koelstra et al., 2011)
	9	Turkish COVID-19 data	2020/3/27-2020/6/11	1d	(Koc and Türkoglu, 2022)
	9	COVID-19 dataset of Orissa state	2020/1/30-2020/6/11	1d	(Dash et al., 2021)
Transportation	207	METR-LA	2012/3/1-2012/6/30	5m	(Cai et al., 2020)
	325	PeMS-BAY	2017/1/1-2017/5/31	5m	(Cai et al., 2020)
	-	BJER4	2014/7/1-2014/8/31	5m	(Yu et al., 2017)
Meteorology	6	Daily data of Shenzhen	from 2015	-	(Chen et al., 2022)
	-	CHIRPS	1981-2015	-	(Funk et al., 2015)
	-	WeatherBench	-	-	(Rasp et al., 2020)
Economics	5	S&P500	1997/1/1-2016/12/1	1d	(Lee and Yoo, 2020)
	13	NSE stocks data	1996/1/1-2015/6/30	1d	(Hiransha et al., 2018)
	6	NYSE stock data	2011/1/3-2016/12/30	1m	(Hiransha et al., 2018)

#### A.6.4 M6

The dataset <sup>10</sup> comprises two categories of assets: one selected from the Standard & Poor's 500 Index, consisting of 50 stocks, and the other comprising 50 Exchange-Traded Funds (ETFs) from various international exchanges. The focus of the M6 competition lies in forecasting the returns and risks associated with these stocks, along with investment decisions made based on the aforementioned predictions.

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<sup>10</sup><https://mofc.unic.ac.cy/>