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Timetable Based Day Ahead Energy Forecasting With Transformers

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Keywords: forecasting, day-ahead load forecasting, timeseries transformer, timetable-based information

Effective day-ahead load forecasting (DALF) is critical to the management of electricity grids and associated energy markets, enabling efficient planning and optimization of power generation and distribution. Furthermore, DALF is essential for resource allocation, reducing the risk of power outages and playing a key role in the environmentally sustainable and cost-optimized operation of power plants. Due to its significance, grid operators aim to ensure reliable DALF while minimizing extreme outliers, which are particularly challenging to compensate for during operation. Many operators still rely on well-established methodologies, such as linear regression models for DALF due to their reliability. However, while these models are reliable, they cannot effectively include detailed next-day contextual information (NDCI) of the forecasting period, such as consumer demand patterns, often resulting in subpar performance. Recent advancements in long-range time-series transformers (TST) are promising for enhancing DALF. The most recent TST demonstrate exceptional performance on standard power forecasting datasets. However, this line of research has no focus on the incorporation of NDCI. In this work, we bridge this gap by proposing an effective method for integrating NDCI with load forecasting using transformers for the DALF scenario. Along with this publication, we release a new, openly available dataset of the Swiss traction power grid with timetable-based NDCI to benchmark our DALF method. Our findings indicate a significant improvement in forecasting accuracy with the use of our NDCI-enhanced transformer model, which has substantial implications for power grid management. Compared to the NDCI-free transformer, the inclusion of NDCI in transformer resulted in a 22% reduction in the Mean Absolute Error (MAE) for DALF, which is associated with a 13.6% improvement in MAE compared to the regression model baseline (EUB).

To maintain power grid stability, the amount of energy consumed (demand) must closely match the energy produced (supply) at any given moment. A key challenge, therefore, is to store and effectively release electrical energy. In large-scale power grids, energy storage is facilitated through hydroelectric means and, more recently, grid-connected battery or hydrogen storage systems. To ensure the safe and efficient operation of these storage systems, operators must have the best possible information about the future behavior of the electricity grid to balance out surplus or deficit energy between partners and therefore employ DALF. However, consumer demand patterns are diverse and difficult to forecast. One remedy for this challenge is that many consumer behaviors depend on plans that are available ahead of time in the form of NDCI. However, conventional forecasting algorithms, often used by operators, do not allow for the efficient integration of such plans. In the domain of traction power grids, where DALF is heavily used, the train schedule (timetable) is one of the most relevant pieces of information for the next day. This work presents a method to integrate such timetable-based information into TST for load forecasting in traction power grids. Current literature on TST focuses on broad applicability and has largely overlooked the incorporation of specific timetable-based information into deep learning models. We therefore focus on evaluating the effectiveness of incorporating NDCI into these models for more accurate predictions.

We adapt TSTs' encoder and decoder embeddings $\boldsymbol{E} \in \mathbb{R}^d$ for the problem of DALF. This adaptation involves combining the embedded contextual information (NDCI) e_{ci}^{t+1} for the day ahead, with temporal embeddings (e_t) and load data embeddings (e_b): $\boldsymbol{E}^{enc} = f(e_t, e_b, e_{ci}^{t}), \boldsymbol{E}^{dec} = f(e_t, e_{ci}^{t+1})$. The forecast is then computed as: $x^{t+1} = TST(\boldsymbol{E}^{enc}, \boldsymbol{E}^{dec})$. We test this approach on two state-of-the-art (SOTA) TST models, Spacetimeformer (STF, Grigsby, J. et al) and Crossformer (CF, Zhang et al, 2022).

To demonstrate the positive impact of integrating NDCI, we have collected a grid load dataset for the Swiss traction power grid operated by SBB. Besides the consumed energy, this dataset contains timetable-based NDCI information such as freight transport in gross tonne-kilometers, the number of trains on the railroad network, and freight tonnages. The data set ranges from 2020 to 2023 with a time resolution of 1h.

We report the performance of NDCI-enhanced TFT for the test period of 2023 Q1/2 in Figure 1 and Table 2. Additionally, we perform an ablation study of NDCI in Table 1 and demonstrate that the presented NDCI-enhanced STF is less susceptible to outliers than the EUB baseline currently in production at SBB in Figure 2.

Table 1. Ablation Study: removing the contextual information has a strong impact on the STF performance (normalized scores).

Model	NMSE	NMAPE	NMAE
STF (w/o TTI)	9.35e-4	4.98%	2.17e-2
STF	4.82e-4	3.98%	1.68e-2

Table 2. Relative improvement for MAE, MAPE, and MSE on the test set (2023 Q1/2) with respect to the EUB model.

Model	MAE	MAPE	MSE
CF	8.48%	9.07%	14.25%
STF	13.63%	12.73%	23.24%

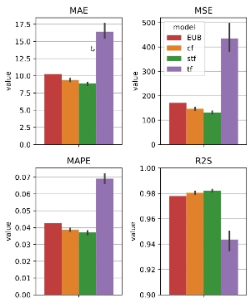

Figure 1. Comparison of STF and CF performance compared with the regression model (EUB) and the standard transformer (tf) on the test set (2023 Q1/2) including coefficient of determination (R2S). The baseline transformer (tf) is not competitive with the well-tuned EUB model. However, SOTA TST combined with NDCI (green) outperform the baseline (EUB).

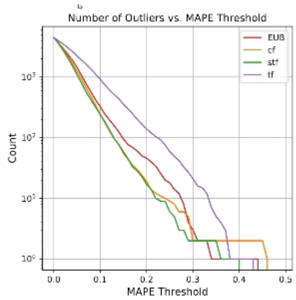

Figure 2. The NDCI-enhanced STF (green) is more reliable than the other methods, resulting in the least amount (counts) of forecasting outliers across different MAPE thresholds.

This research highlights the potential of time-series transformer, augmented with NDCI, to improve DALF. It underscores the necessity of adopting advanced forecasting methods in the energy sector to increase forecast reliability and to address the growing complexity of grid management.

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Digital Twin For Maintenance: Overview And Trends

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Keywords: Digital Twin, maintenance, overview, trends, Industry 4.0

This article examines the evolution of Digital Twin (DT) technology from 2017 to 2023, highlighting its increasing importance and diversified application, especially in maintenance. A significant advancement is the integration of Augmented Reality (AR) and Virtual Reality (VR) technologies since 2021, significantly improving the DT experience. Research, predominantly conducted in Europe and Asia, shows a diversification of DT applications beyond the industrial sector, encompassing civil engineering, healthcare, energy, and transportation. The article emphasizes the transformative impact of DTs in maintenance strategies, anticipating their continuous evolution and growing relevance across various sectors.

As the industrial landscape continuously evolves, Digital Twin (DT) technology has emerged as a game-changer. Building upon insights from the 2020 study, "Digital Twin for Maintenance: A Literature Review," our article delves into the transformative period from 2017 to 2023. We meticulously analyzed 272 articles sourced from Google Scholar, focusing on titles with specific keywords to uncover the latest trends and breakthroughs in DT technology. A noteworthy development since 2021 is the seamless integration of Augmented Reality (AR)/Virtual Reality (VR) and Multiple-Criteria Decision Analysis (MCDA) technologies, significantly enhancing DT applications.

Post-2017, we've witnessed an exponential increase in digital twin research, highlighting its escalating significance across multiple sectors. This trend is not merely in quantity but also in the quality and sophistication of the solutions. The integration of VR technologies (Heuser et al., 2022) and AR technologies (Wei et al, 2021) since 2021 marks a significant leap, transforming digital twins into more intuitive and user-friendly tools. These advancements in visualization and interaction capabilities are revolutionizing monitoring and maintenance strategies. The adoption of MCDA methodologies also signifies a shift toward more complex and multi-dimensional decision-making in maintenance management (Yu et al., 2021).

Geographically, the majority of digital twin research originates from Europe and Asia, accounting for an astounding 84% of total publications. China's substantial contribution, representing 34% of the total, underscores the technological prowess and commitment of these regions to advance DT applications in maintenance. The European research landscape is notably diverse, with significant contributions from the UK, Germany, Italy, and France, demonstrating their robust approach to DT research and development (Table 1). Sector-wise, the industrial domain remains the primary beneficiary of DT technology. However, there's an emerging trend of diversification.

The rise in applications within civil engineering, which now accounts for 7% of the studies, signals DT's expansion beyond traditional manufacturing realms to include maintenance of infrastructure, buildings, and bridges. Moreover, the technology is steadily penetrating sectors like healthcare, energy, and transportation, collectively comprising 6% of the literature. This diversification underscores the versatile utility of digital twins and their potential to revolutionize maintenance strategies across various industries.

Digital twins in maintenance have transcended predictive maintenance, becoming integral to various strategies including condition-based, reliability-oriented, and proactive maintenance. These models are pivotal not just in forecasting potential issues, but in actively shaping maintenance schedules and activities through real-time data and risk assessments. In advanced applications, digital twins are even recommending or autonomously implementing solutions to mitigate risks and prevent failures, showcasing their adaptability and transformative impact across sectors. The incorporation of AR and VR technologies since 2021 represents a significant advancement in the digital twin arena (Figure 1). These immersive tools offer more intuitive and interactive platforms for maintenance, facilitating a deeper understanding and more effective management of complex systems. This technological progression isn't just a testament to innovation in digital twin applications but also hints at the future trajectory of this field, promising enhanced efficiency and continued progress.

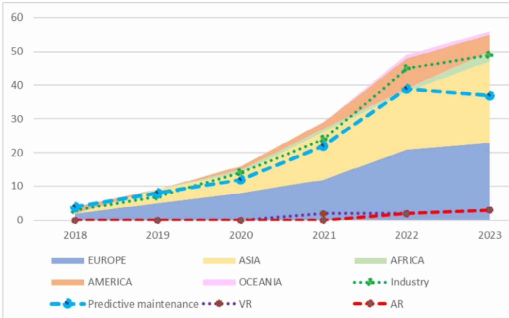

Fig. 1. Digital Twins and related technologies trends in different continents.

Table 1. Summary of the selected papers for the study and their classifications.

	2018	2019	2020	2021	2022	2023	Total	%
EUROPE	2	5	8	12	21	23	71	44%
ASIA	0	4	6	14	17	24	65	40%
AFRICA	0	0	1	1	1	3	6	4%
AMERICA	2	0	1	2	9	5	19	12%
OCEANIA	0	0	0	0	1	1	2	1%
	4	9	16	29	49	56	163	100%
Industry	3	7	14	24	45	49	142	87%
Civil Engineering	1	2	1	3	2	3	12	7%
Other	0	0	1	2	2	4	9	6%
	4	9	16	29	49	56	163	100%
Predictive maintenance	4	8	12	22	39	37	122	75%
Preventive maintenance	0	0	2	4	7	9	22	13%
Systematic maintenance	0	1	1	2	1	5	10	6%
Conditional preventive maintenance	0	0	1	1	2	5	9	6%
	4	9	16	29	49	56	163	100%
VR	0	0	0	2	2	3	7	4%
AR	0	0	0	0	2	3	5	3%

In conclusion, our study not only reaffirms but also expands upon the findings of previous literature, emphasizing the evolution of the digital twin as an indispensable tool in maintenance. The post-2017 era is marked by a diversification in application and a broadening of scope, with digital twins becoming increasingly essential in varied maintenance strategies. The integration of technologies like AR and VR has enriched the digital twin experience, elevating decision-making within maintenance practices. While our focused research approach has narrowed the scope to a subset of available studies, it has effectively captured the essence of this transformative technology. The industrial sector continues as the primary beneficiary, especially in manufacturing with the rapid adoption of Industry 4.0 innovations. Nevertheless, the escalating relevance of digital twins in civil engineering and other sectors is undeniable. This study not only corroborates foundational ideas from earlier literature but also illuminates the evolving utility of digital twins as a comprehensive tool for advanced maintenance strategies across diverse industries.

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