Probabilistic Time-Series Crowd Forecasting at Scheveningen Beach, The Netherlands

Theivaprakasham Hari*[1], Winnie Daamen[1], Yanan Xin[1], Sascha Hoogendoorn-Lanser[1], Jeroen Steenbakkers[2], and Serge Paul Hoogendoorn[1]

[1]Delft University of Technology, The Netherlands, 2618 CN
[2]Argaleo B.V, 's-Hertogenbosch, The Netherlands, 5223 AL

Abstract
Accurate forecasting of visitor crowd count enables crowd safety managers, municipal authorities, and organizers to anticipate potential risks, deploy personnel strategically, and implement timely interventions. Using the case study at Scheveningen beach, Netherlands, we propose a probabilistic approach, using Conformalized Quantile Regression (CQR) to generate reliable uncertainty prediction intervals for the 14-day hourly forecast. Compared to the quantile regression method, CQR offers better coverage reliability. Our study improves uncertainty quantification of crowd forecasting, supporting crowd management in a dynamic beach environment

Keywords Pedestrian Crowd forecasting, Uncertainty Quantification, Probabilistic forecasting, Conformal prediction, Crowd management

Problem Statement and Objectives

Effective crowd management is critical for ensuring safety, optimizing resources, and enhancing visitor experiences. Accurate and reliable crowd forecasting is integral to the success of crowd management. For example, a 14-day hourly forecast provides valuable information for mid-term planning at tourist destinations such as Scheveningen Beach, Netherlands. Over this time frame, crowd safety managers need reliable staffing, logistics, security arrangements, and resource procurement estimates. In addition to improving forecasting accuracy, quantifying the uncertainty of predictions has garnered increasing attention from researchers and practitioners as it enhances the reliability and explainability of forecasting outcomes.

Traditional forecasting methods (e.g., linear or autoregressive models) often fail to capture these dynamics and struggle with reliable uncertainty estimation. Probabilistic forecasting methods such as Quantile Regression (QR) and bootstrapped residual approaches face limitations in extrapolation and computational efficiency [1]. To overcome these issues, this study applies Conformalized Quantile Regression (CQR), a distribution-free probabilistic approach providing robust uncertainty quantification, to generate reliable 14-day hourly crowd forecasts [2]. Our objectives are to evaluate CQR's performance against standard methods (QR and bootstrapping) regarding prediction interval coverage, interval width, and computational feasibility, specifically to enhance planning and risk mitigation at Scheveningen Beach, Netherlands.

Methodology

A time-stamped dataset, comprising historical visitor counts, weather features (e.g., temperature, rainfall, wind), and calendar variables, was chronologically split (80:15:5) into training, calibration, and testing sets. We trained XGBoost and LightGBM models and their quantile versions (10th and 90th quantiles) using grid-search tuning to minimize errors on the training set. As baselines for uncertainty, we employed (i) Quantile Regression (QR), directly producing upper/lower bounds, and (ii) a bootstrapped residual approach, sampling from past residuals to approximate prediction intervals. CQR further refined the quantile estimates: residuals from the calibration set were used to derive non-conformity scores and adjust interval widths, ensuring empirical coverage at the desired nominal level. Finally, performance on the test set was evaluated using Mean Interval Coverage (MIC), Mean Interval Width (MIW), and the Mean Interval Winkler Score (MIWS).

*Email of the corresponding author: t.hari@tudelft.nl

Table 1: Performance metrics for different uncertainty estimation methods applied to XGBoost and LightGBM forecasting models with prediction interval 0.10-0.90 quantiles

Methods	XGBoost			LightGBM		
80% Prediction Interval (10th - 90th Quantile)	**Mean Interval Coverage**	**Mean Interval Width**	**Mean Interval Winkler Score**	**Mean Interval Coverage**	**Mean Interval Width**	**Mean Interval Winkler Score**
Bootstrapped Residual	0.67	1317.8	2610.4	0.72	1418.41	2435.70
Quantile Regression	0.80	1601.76	2637.27	0.81	1439.26	2415.87
Conformal Prediction	0.81	2052.40	3558.24	0.87	2075.12	3423.75
Conformalized Quantile Regression	0.83	1438.69	2561.92	**0.87**	**1401.38**	**2312.28**

Results and Discussion

Our results (Table 1, Figure 1) demonstrate clear advantages of Conformalized Quantile Regression (CQR) for crowd forecasting at Scheveningen Beach. The MIC evaluates how frequently actual visitor counts fall within predicted intervals (target coverage of 0.80), MIW measures interval precision (narrower is better), and MIWS assesses overall prediction quality (lower scores indicate higher accuracy and precision). Based on these metrics, the bootstrapped residual method underestimated prediction uncertainty, showing coverage below the desired 0.80, potentially causing inadequate preparedness during unexpected visitor increases. Naive Quantile Regression and standard Conformal Prediction methods generated overly broad intervals, indicated by larger interval widths and higher MIWS, making precise resource planning difficult. Figure 1 shows clear visitor peaks, representing periods of significantly increased attendance. CQR effectively captures these peaks with narrower intervals and meets the desired metrics (e.g., the peak on 2023.11.11), enabling managers to anticipate high-attendance periods and to make informed decisions about resource allocation, risk mitigation, and strategic planning.

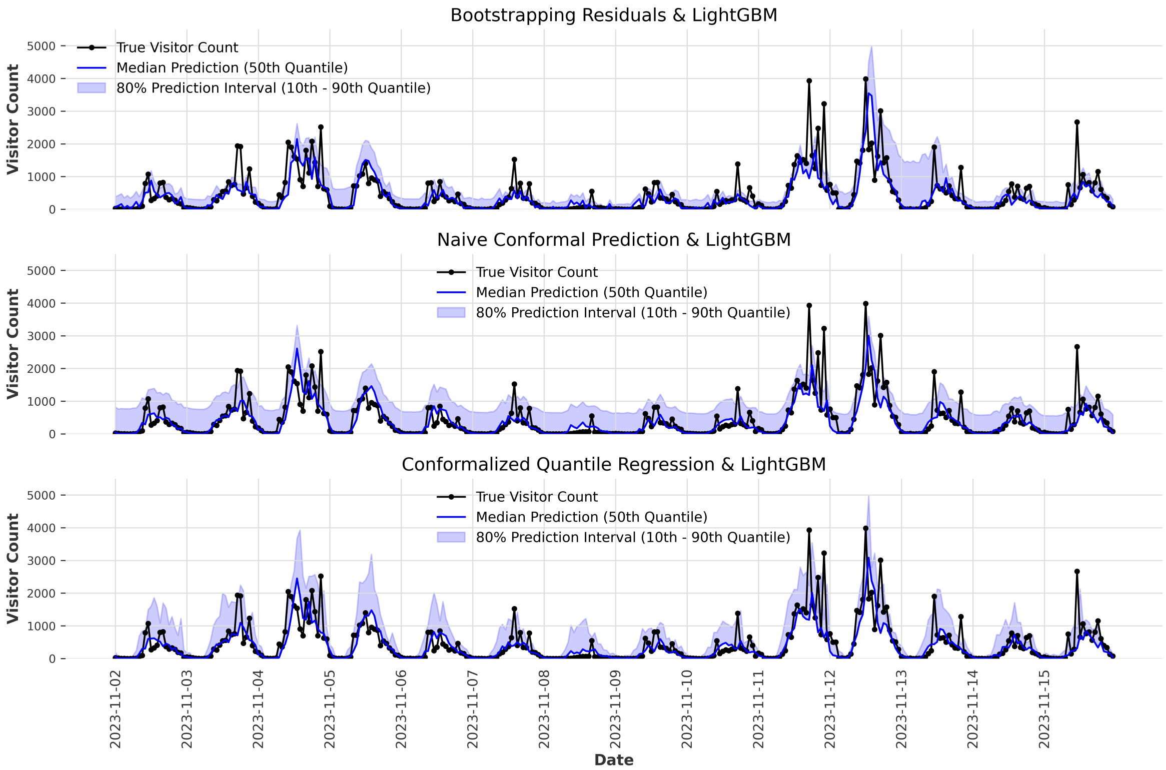

Figure 1: Comparison of 14-Day visitor crowd forecasts with different uncertainty estimation

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