Methods (cont.)

where $\delta y_i$ is a $k \times 1$ vector of the differenced series $y_i - y_{i-1}$, $\Pi = (I - \Phi_1 - \cdots - \Phi_p)$ and $\Gamma = (I - \Psi_1 - \cdots - \Psi_q)$ (for $i = 1, \ldots, p - 1$).

The model has the following assumptions:

- Assumption 1: The components of $y$ are at most $I(1)$, i.e., integrated of order 1.
- Assumption 2: $0 \leq r = \text{rank}(\Pi) \leq k$
- Assumption 3: $\Pi$ and $\Gamma$ are identically and independently distributed $N(0, \Sigma)$ random vectors with covariance matrix $\Sigma$.

For assumption 2, if $r = k$, then it can be shown that the VECM becomes a standard VAR model. If $r > 0$, then $\Pi$ is the zero matrix and there is no cointegration relationship between the series. The VECM then becomes a VAR model for differenced time-series. If $0 < r < k$, then $\Pi$ can be factored into $\Pi = ap^T$, where $a$ and $\beta$ are both $k \times r$ matrices. From assumption 1, the differenced series $\delta y_i$, and its lag $\delta y_{i-1}, \ldots, \delta y_{i-p}$, are stationary. It follows that $\Pi y_i = ap^T y_{i-1}$, also called the error correction term, is (trend-)stationary, depending on the specification of the deterministic components of the $r$ linearly independent columns of $\beta$ are the cointegrating vectors and the rank $r$ to equal to the cointegration rank of the system of time series.

Forecast performance

We used Mean Absolute Percentage Error (MAPE) to evaluate the 7-day-ahead forecasts of Census:

$$\text{MAPE} = \frac{100 \sum_{t=1}^{T} |y_t - \hat{y}_t|}{\sum_{t=1}^{T} |y_t|}$$

where $\hat{y}_t$ is the forecast value and $y_t$ is the actual value.

The sampling distribution of out-of-sample MAPE is obtained by bootstrapping the MAPE values.

Long-range scenario-based forecasting

Leveraging epidemiologically informed scenarios of the future infection incidence, we attempted to use the model to create realistic projections of hospital census. On January 9, 2021, we expected the winter surge to reach peak infection prevalence around February 5, 2021 based on an extension of an epidemiological model called the Susceptible-Infected-Removed model [2]. We linearly extrapolated Incidence with positive trend up to the expected pandemic peak. The severity of a scenario was controlled by a trend-dampening parameter [3]. After the peak, the descent path was initially symmetric to its ascent and then eventually became linear (Figure 2).

Model evaluation

The level equation requires 7 lags ($p = 7$) to capture all temporal dependencies.

Strong evidence for a cointegration relationship ($P < 0.01$).

- Short-run effects: past incidence changes at lags 1, 2, 4, 5, and 6, as well as past Census change at lag 2, had significant effects on Census change.

Forecast performance

- The typical value (median) of MAPE was 5.9% and the 95th percentile of MAPE was 13.4% (Figure 3). For the sake of comparison, the corresponding values from an Autoregressive Integrated Moving Average (ARIMA) model using the COVID-19 hospital census only were 6.6% and 14.3%.

Figure 3. Distribution of the 7-day-ahead Mean Absolute Percentage Error from time-series cross-validation for the period June 16, 2020 - November 28, 2020. Median (blue), 95th percentile (red).

Discussion

- We have ascertained the long-term stable relationship between local infection incidence and COVID-19 hospital census. Whereas, current models, e.g., the COVID-19 Hospital Impact Model for Epidemics (CHIME) [4], rely on simplified assumptions about the relationship.

- Local infection incidence shows to be an effective leading indicator for COVID-19 hospital census, through both short-run and long-run effects, and as demonstrated by very good forecast performance against the traditional ARIMA model.

- In hindsight, by evaluating different scenarios of peak resource demand against our resource capacity, we have correctly assured our leaders of our capability to handle even the worst-case scenario, alleviated uncertainty, and effectively guided long-term planning of adequate staffing, bed capacity, and equipment supplies through the pandemic.

Resources


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This research protocol was submitted to the Atrium Health Institutional Review Board (IRB) prior to execution and the study was deemed exempt from IRB oversight. In compliance with HIPAA regulations, individual patient information is not disclosed, all data have been deidentified and reported as aggregates.