

MTHM506 Statistical Data Modelling Group Project

Analysis of 2012–2014 Brazil Tuberculosis Data

Group 2

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1 Introduction

1.1 Problem Statement

Analysis of tuberculosis (TB) data originating from Brazil using Generalized Additive Models (GAMs). Brazil is divided into 557 administrative microregions, and the available data comprises counts of TB cases in each microregion for each of the years from 2012 to 2014.

1.2 Exploratory Analysis of Data and Problem

The TB data from Brazil includes 1,671 entries or samples with 14 columns of numeric data types that specify the characteristics of each sample. The columns are self-explanatory because they are called Indigenous, Illiteracy, Urbanisation, Density, Poverty, Poor Sanitation, Unemployment, Timeliness, Year, TB, Population, Region, lon, and lat. TB stands for tuberculosis, whereas lon and lat stand for longitude and latitude. The dataset has no missing values in the technical sense, but it contains some abnormalities, which increases the amount of pre-processing needed. The region is stored as a continuous variable despite being a factor variable. Nonetheless, changing it depends on the task at hand. Moreover, the collection includes coordinates that describe the precise geospatial locations of the micro-regions listed in the column. The next part gives a detailed exploration of the data.

1.3 Data Exploration

An in-depth analysis of the datasets reveals that the mean and median values for the indigenous population are low, but the maximum value is 50, which suggests that there are individual areas where the indigenous population is concentrated and that these areas may be areas of potential poverty and poor sanitation and should be areas where there are more cases of tuberculosis. The mean and median illiteracy rates are only 14 and 11, respectively. However, the maximum value of 41 suggests that there are specific backward areas with significant populations lacking access to education, which also suggests that the area seems poor and has poor sanitation. There are still some places that are less urbanised, where there may be more occurrences of tuberculosis, but the mean, median, and minimum values for urbanisation are 70 and 22, respectively, suggesting that most areas are highly urbanised. Based on the population density data, most locations can fit one person in a room, but the highest value of 1.6 highlights the existence of some places with very high population densities, which sharply raise the rate of TB transmission. The distribution of the poverty data suggests that each district has different poverty levels, with only a limited number of districts where poverty is not a significant issue. Although the general results on inadequate sanitation are low, the maximum score of 58 indicates that some districts have poor sanitation and substantial disease risk. Although average unemployment rates are low, a maximum value of 20 indicates that some isolated regions may experience severe economic hardship, protracted social unrest, and potentially significant morbidity rates. With a minimum value of 0, notification timeliness data has a fairly wide range.

Timeliness, Unemployment, and Urbanization approximately follow a Normal Distribution with few extremes, whilst the remainder is multimodal normal distributions. The above suggests that employing semi-parametric or non-parametric models to demonstrate the relationship between the target and predictors would be advantageous. The target variable in this study is a risk, defined as 'TB/Population', whereas the remaining variables are possible predictors. As demonstrated in Figure 5, most features in the dataset exhibit some connection. As some features are correlated, basic regression cannot be used because it would yield false results; rather, models that account for the

connection can be used. It is vital to note that some characteristics are anticipated to have positive correlations (tuberculosis versus population, density versus poverty) and vice versa. Specifically, population density, poverty, health conditions, unemployment, and notification timeliness are likely high due to the high population density, the low economic share per capita, the high poverty rate, and the high jobless rate. See Figure 5 for a correlogram of the 8 socio-economic covariates

2 Model

We want to model the count of cases TB_i by actually modelling ρ_i using

$$TB_i \sim Pois(\lambda_i = z_i \rho_i) \quad TB_i \text{ indep.} \\ \log(\lambda_i) = \log(z_i) + \log(\rho_i)$$

where TB_i is the count of TB cases. We are using the canonical link function - log. z_i is the total population, which is taken as an offset. Model $\log(\rho_i)$ as

$$\log(\rho_i) = \sum_{j=1}^8 f_j(x_{i,j}) \\ f(x_i) = \sum_{k=1}^q \beta_k b_k(x_i)$$

where $x_{i,j}$ is the j th covariate (out of 8 socio-economic covariates) for the i th instance/datum in the dataset, $f(\cdot)$ is a smooth function of said covariate and $b_k(\cdot)$ is a basis function with k knots. Hence, the model boils down to

$$TB_i \sim Pois(\lambda_i = z_i \rho_i) \quad TB_i \text{ indep.} \\ \log(\lambda_i) = \log(z_i) + \sum_{j=1}^8 \sum_{k=1}^q \beta_{j,k} b_{j,k}(x_{i,j})$$

Looking at the distribution of the residuals of the model, we can see that the data is clearly far too overdispersed to be modelled by a Poisson, which has a fixed dispersion parameter. Even with 60 knots per smooth term the model doesn't seem to have enough flexibility which may be another indicator that a Poisson model is unsuitable for the data. The residuals vs fitted plot fans out, indicating that the model does not have enough flexibility to fit well (the edf is also close to the maximum degrees of freedom, and increasing the number of knots doesn't resolve the problem). We propose the conventional alternative to the Poisson - the Negative Binomial model. Doing so, leads to a drop in the AIC. So the model distribution is changed to Negative Binomial with the same parameterisation except for the feature that the count of TB cases is now Negative Binomial distributed with mean as described above. See Table 1 appendix for a showcase of different model configurations and their associated AIC.

$$TB_i \sim NB(\lambda_i, \sigma_i^2) \quad TB_i \text{ indep.} \\ \lambda_i = z_i \rho_i; \quad \sigma_i^2 = \lambda_i + \frac{\lambda_i^2}{\phi} \\ \log(\lambda_i) = \log(z_i) + \sum_{j=1}^8 \sum_{k=1}^q \beta_{j,k} b_{j,k}(x_{i,j})$$

where ϕ is a dispersion parameter, later estimated by the `gam` function in R.

When having a look at the relationship between the squared residuals and the fitted values one sees that the relation is not exactly quadratic, but rather close to 0, which would reflect the relation between model variance and the expected value in a Gaussian Distribution Model (additional evidence is provided by the Residuals vs. Fitted plot). However, fitting a Gaussian model leads to very skewed residuals, indicating that the data is apparently not Gaussian. So the model distribution is changed to Negative Binomial with the same parameterization except for the feature that the count of TB cases is now Negative Binomial distributed with mean λ_i as described above.

Given this base model, we investigate whether all given socio-economic variables are needed to explain the response or whether there exists a model with fewer parameters. The p-value for the

smooth term of Illiteracy points towards it not being statistically significant. Poverty, although not statistically insignificant, has the second-largest p-value. These terms are sequentially dropped and the resulting model checked against the original model via a Likelihood Ratio Test (conducted using the `anova` function in R). We find that leaving out Illiteracy does not alter the model at a 5%-level of significance, whereas taking out both Poverty and Illiteracy does. So, in the following, we use a model with all of the socio-economic variables except Illiteracy. Note that this converts our linear predictor to

$$\log(\lambda_i) = \log(z_i) + \sum_{j=1}^7 \sum_{k=1}^q \beta_{j,k} b_{j,k}(x_{i,j})$$

This leaves us with a model with AIC = 14,391.19 and 43.9% of deviance explained. Running `gam.check()` lets us analyse the residual plots (see Figure) and examine the basis functions for the model. The QQ plot tells us that the model fails to predict well on the upper and lower ends of the response variable. Increasing the knots to 20 per covariate leads to marginal improvement with 44.9% deviance explained. More efficient extensions can be to add 1) spatial, 2) temporal and 3) spatio-temporal covariates.

First, we will try adding spatial terms. The spatial model adds a smoothed term which is function of the longitude and the latitude. A bivariate function is used because it makes sense to assume that there are more cases at certain locations (defined by the interaction between latitude and longitude) than others, rather than there being more cases at locations with a certain longitude for any latitude, or the other way round. Hence, our linear predictor is now

$$\log(\lambda_i) = \log(z_i) + \sum_{j=1}^7 \sum_{k=1}^q \beta_{j,k} b_{j,k}(x_{i,j}) + \sum_{k=1}^q \beta_k b_k(\text{lon}_i, \text{lat}_i)$$

Using this model with the regular `s` smoother function from the `mgcv` package leads to a model that can explain 56.4% of the deviance and has a slightly lower AIC of 14,013.13. The QQ plot still points to the upper and lower tails being incorrectly predicted. At the cost of significantly more computation, using a tensor product smooth `te` on the bivariate spatial term with 20 knots allows us to make a decent improvement on this. See Appendix for different numbers of knots that were tested. This gets us to 69.9% deviance explained. The QQ plot looks considerably better with only a few problematic instances at the top and bottom quantiles.

We contest this with an extension on the model with only socio-economic covariates, but instead of adding spatial terms, we add the temporal dimension **Year**. The linear predictor becomes

$$\log(\lambda_i) = \log(z_i) + \sum_{j=1}^7 f_{2012,j}(x_{i,j}) \times x_{2012} + \sum_{j=1}^7 f_{2013,j}(x_{i,j}) \times x_{2013} + \sum_{j=1}^7 f_{2014,j}(x_{i,j}) \times x_{2014}$$

where the new terms $x_{2012}, x_{2013}, x_{2014}$ are indicator variables equating to 1 if **Year** is respectively 2012, 2013, 2014 and zero otherwise. Exercising some shorthand, it can be expressed as

$$\log(\lambda_i) = \log(z_i) + \sum_{t=2012}^{2014} \sum_{j=1}^7 f_{t,j}(x_{i,j}) \times x_t$$

where x_t is now the indicator variable for **Year**. A slightly separate approach can be tested with **Year** as a covariate instead of a grouping variable. In that case, the linear predictor would be

$$\log(\lambda_i) = \log(z_i) + \sum_{j=1}^7 f_{t,j}(x_{i,j}) + \sum_{t=2012}^{2014} \beta_t x_t$$

Neither of the temporal formulations show much increase in deviance explained (the one with year as grouping variable actually shows a decrease to 41.5%!). Their QQ plots are also much worse than the spatial model, showing gross deviations on high as well as low quantiles. Finally, we create a spatio-temporal model, including both **Year** as well as **lon, lat**. Its linear predictor is formulated as below

$$\log(\lambda_i) = \log(z_i) + \sum_{t=2012}^{2014} \left(\sum_{j=1}^7 \sum_{k=1}^q \beta_{t,j,k} b_{t,j,k}(x_{t,i,j}) + \sum_{k=1}^q \beta_{t,k} b_{t,k}(\text{lon}_{i,t}, \text{lat}_{i,t}) \right) \times x_t$$

This is a model which includes the term for the location and estimates a functional relation for each year and each explaining variable. The AIC of this model does not drop compared to the spatial model. Reasons for this may be that 3 factors is perhaps not enough granularity to discern any effect from the temporal dimension. Naive estimates would point towards the spread being higher in winter months as TB spreads through inhaling tiny droplets from coughs or sneezes. Having more granular data at the season or month level could bring to light any temporal patterns, if they exist.

So the spatial model (given that it is simpler) is the model we choose to best explain the ratio of TB cases per capita. To recall, it is formulated as

$$\log(\lambda_i) = \log(z_i) + \sum_{j=1}^7 \sum_{k=1}^q \beta_{j,k} b_{j,k}(x_{i,j}) + \sum_{k=1}^q \beta_k b_k(\text{lon}_i, \text{lat}_i)$$

Considering the fit of the spatial model, it fits well even though the largest residuals are higher than expected from the model distribution. For districts that have a high number of cases, the predictor does not seem as accurate. But the highest residuals do not arise when the ratio of TB cases per capita is extraordinarily high, but rather when the absolute number of TB cases is high (see residuals vs. response). The variance of the model still seems too low for those values given that there are some predicted values in that high segment of response values (absolute number of TB cases) where the prediction for the response value is lower than the actual value, and some where the prediction of the actual value is higher than the actual value. Using this model, we predict the rate of TB per 100,000 inhabitants. See Figure 1

3 Critical Review

Drawbacks of the Model:

1. Predictions do not cover full range of data, as evinced by deviations in the QQ plot
2. The independence assumption of the **Year** variable can be questioned in two ways, thus providing justification for leaving it out: The data points of a certain district in 2012, 2013 and 2014 may not be fully independent of one another because it is likely that the conditions in that region have not substantially changed. The model seems unnecessarily complex, if we add additional smooth terms for each variable grouped on **Year** - it hardly brings any additional explanatory power. Another possible violation of the independence assumption arises from spatial correlation - the fact that regions which are located closely to one another are mutually dependent of one another in terms of the number of TB cases as well as the socio-economic determinants of the spread of infectious diseases. Parametric coefficients of the **Year** factor in `temporal.model` barely differ from each other, at around -8.4 for **Year**=2012, and varying by 0.004 and -0.038 respectively for 2013 and 2014, which respectively correspond to multipliers of 1.004 and 0.963 on the response scale.
3. The fitted vs. response plot shows a deviance from the 45-degree line for high absolute values of the number of cases. One reason for this is that the model is designed to predict the ratio of TB cases per capita, not the absolute number. Another reason is that the model variance increases with the mean value.

4 Conclusions

Firstly, based on the Correlogram we can conclude that no single socio-economic covariate has much linear correlation with TB incidence, but illiteracy, urbanisation, poverty, sanitation, unemployment and timeliness of notification are all weakly correlated with TB incidence, and given that there are more strong correlations between these socio-economic covariates, an increase in illiteracy, poverty, unemployment and poor sanitation will simultaneously correlate to decreases in urbanisation and timeliness of notification, all contributing to increases in TB incidence. Poverty is strongly correlated with several socio-economic covariates and is the primary factor that governments need to improve. Sanitation and urbanisation are also more strongly correlated, implying that good urban infrastructure and quality health resources have a greater impact on reducing TB incidence. According to our predicted TB incidence map, Brazil's central region has a lower incidence overall, so we recommend that the health sector invest significant health resources to improve the current situation throughout Brazil's north-west, followed by localised areas in the south and east, although these areas could also rely on assistance from neighbouring regions with fewer cases to improve their situation.

5 References

1. Wood, S. N. (2017). Generalized Additive Models: An Introduction with R (2nd ed.). CRC Press.

6 Appendix

6.1 Figures

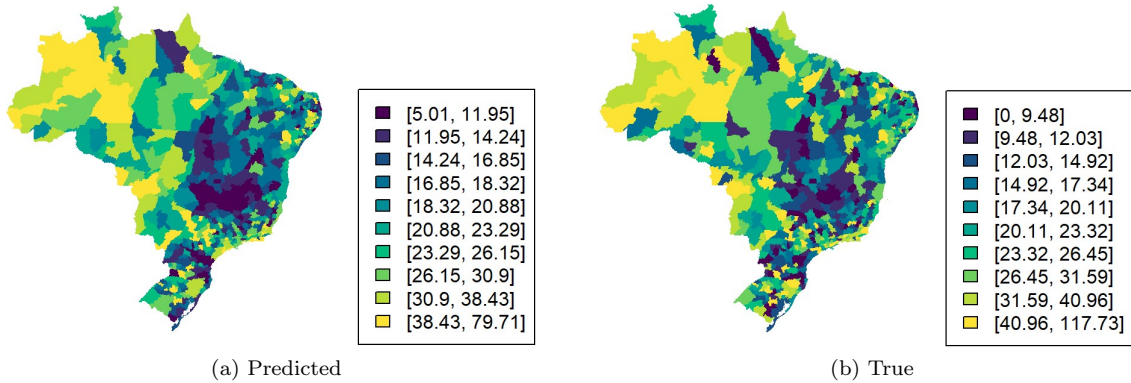


Figure 1: Predicted (a) and True (b) rates of TB per 100k inhabitants. North-western parts of the country as well as parts near the south exhibit high TB incidence per capita. These would roughly correspond to the states (*estados*) of Amazonas in the North-West, Sao Paulo in the South and Rio de Janeiro on the South East coast

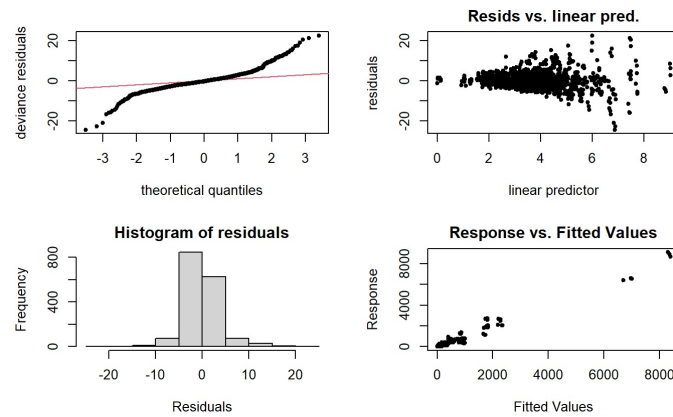


Figure 2: `gam.check()` results for `model_poisson`. The data is overdispersed as can be seen from both the QQ-plot and the fanning of the Resids vs linear pred. plot. The histogram of residuals is also quite different from a gaussian distribution

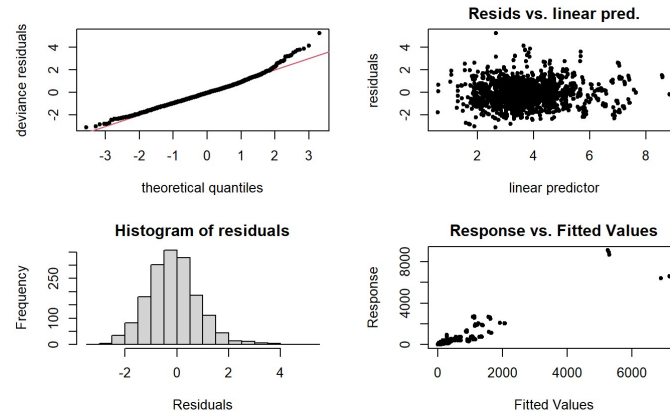


Figure 3: `gam.check()` results for `model_nb.2`. Albeit an improvement of the Poisson model, the model has a tough time correctly predicting values on the upper and lower quantiles

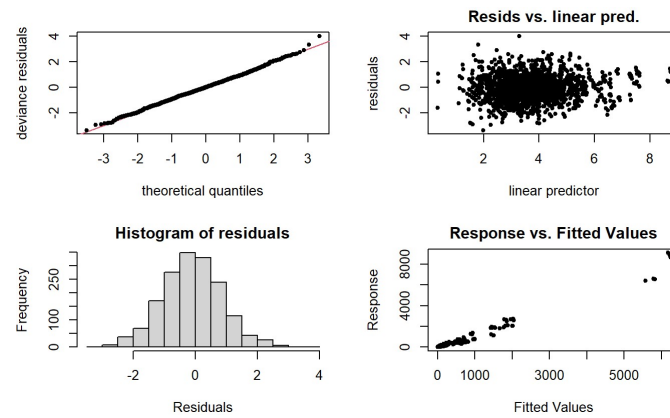


Figure 4: `gam.check()` results for `spatial.model.2`. This is the model that has finally been used as temporal additions on top of this provide very little additional explanatory power

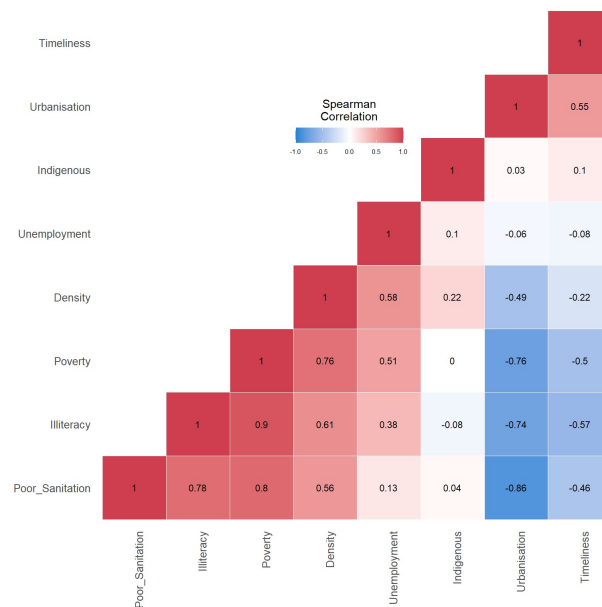


Figure 5: Correlogram shows covariates with highest positive and negative correlations.

6.2 Tables

Model	AIC	Deviance Explained
model_poisson	34047.36	66.9%
model_nb	14391.19	43.9%
model_nb.2	14389.56	43.9%
model_nb.3	14405.00	43.0%
model_nb.time	14389.70	44.0%
temporal.model	14390.43	44.0%
spatial.model	14013.13	56.4%
spatial.model.2	13650.8	69.9%
spatial.model.temporal	14227.12	52.2%
spatial.model.temporal.2	13647.93	70.1%

Table 1: Comparison of models.

6.3 Code

```

1  # Load Data
2  load("datasets_project.RData")
3  # Import Libraries
4  library(mgcv) # required for GAM
5
6  #fit poisson model with socio-economic variables
7  model_poisson <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous)
8  + s(Illiteracy) + s(Urbanisation) + s(Density) + s(Poverty) + s(Poor_Sanitation)
9  + s(Unemployment) + s(Timeliness),
10 data = TBdata,
11 family = poisson(link = 'log')
12 )
13
14 #add flexibility
15 model_poisson.more.knots <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous, k = 60)
16 + s(Illiteracy, k = 60) + s(Urbanisation, k = 60) + s(Density, k = 60)
17 + s(Poverty, k = 60) + s(Poor_Sanitation, k = 60) + s(Unemployment, k = 60)
18 + s(Timeliness, k = 60),
19 data = TBdata,
20 family = poisson(link = 'log')
21 )
22
23 #fit negative binomial model with socioeconomic
24 model_nb <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous)
25 + s(Illiteracy) + s(Urbanisation) + s(Density) + s(Poverty) + s(Poor_Sanitation)
26 + s(Unemployment) + s(Timeliness),
27 data = TBdata, family = nb(link = 'log')
28 )
29
30 #fit a linear relation between squared residuals and prediction to see whether another model describes
31 #the variance-fitted values relation better
32 summary(lm(log(model_nb$residuals^2) ~ log(predict(model_nb, type = 'response'))))
33
34 #drop Illiteracy
35 model_nb.2 <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous) + s(Urbanisation) + s(Density)
36 + s(Poverty) + s(Poor_Sanitation) + s(Unemployment) + s(Timeliness),
37 data = TBdata,
38 family = nb(link = 'log')
39 )
40
41 # Likelihood ratio test
42 anova.gam(model_nb.2, model_nb, test = 'F') # p-value is over 0.05
43 # The models are statistically indistinguishable

```

```

44
45 model_nb_3 <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous) + s(Urbanisation) + s(Density)
46 + s(Poor_Sanitation) + s(Unemployment) + s(Timeliness),
47 data = TBdata,
48 family = nb(link = 'log')
49 )
50 # Likelihood ratio test
51 anova.gam(model_nb_3, model_nb_2, test = 'F')# p-value is less than 0.05
52 # The models are statistically different. Poverty should not be excluded.
53
54 ### Model chosen (with socio-economic covariates) is the negative binomial without Illiteracy
55 ### as the effect of illiteracy cannot be reliably stated to be non-zero
56
57 ##### Introducing temporality as a grouping variable
58 #Temporal model
59 model_nb_time <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous, by = Year)
60 + s(Urbanisation, by = Year) + s(Density, by = Year) + s(Poverty, by = Year) + s(Poor_Sanitation, by = Year)
61 + s(Unemployment, by = Year) + s(Timeliness, by = Year),
62 data = TBdata,
63 family = nb(link = 'log')
64 )
65
66 ##### Temporality as a covariate
67 TBdata$Year.asFactor <- factor(TBdata$Year)
68
69 temporal.model <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous)
70 + s(Urbanisation) + s(Density) + s(Poor_Sanitation) + s(Unemployment) + s(Poverty)
71 + s(Timeliness) + Year.asFactor,
72 data = TBdata ,
73 family = nb(link = 'log')
74 )
75
76 ### Adding spatial covariates
77 spatial.model <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous)
78 + s(Urbanisation) + s(Density) + s(Poor_Sanitation) + s(Unemployment) +s(Poverty)
79 + s(Timeliness) + s(lon , lat),
80 data = TBdata ,
81 family = nb(link = 'log')
82 )
83
84 ### Using separate smoothers
85 spatial.model.2 <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous)
86 + s(Urbanisation) + s(Density) + s(Poor_Sanitation) + s(Unemployment) + s(Poverty)
87 + s(Timeliness) + te(lon , lat , k = 20),
88 data = TBdata ,
89 family = nb(link = 'log')
90 )
91
92 # Check if this model is significantly different from one with only socio-economic covariates
93 anova.gam(spatial.model.2, model_nb_2, test = 'LRT')
94
95 ##### Spatio-temporal model
96 spatio.temporal.model <- gam(formula = TB ~ offset(log(Population)) + s(Urbanisation, by = Year.asFactor)
97 + s(Density, by = Year.asFactor) + s(Poverty, by = Year.asFactor)
98 + s(Poor_Sanitation, by = Year.asFactor) + s(Timeliness, by = Year.asFactor)
99 + s(Unemployment, by = Year.asFactor) + te(lon,lat, by = Year.asFactor), data = TBdata, family = nb(link = 'log'))
100
101 ### Spatio-temporal model (with Year as parametric covariate)
102 spatio.temporal.model.2 <- gam(formula = TB ~ offset(log(Population)) + s(Indigenous)
103 + s(Urbanisation) + s(Density) + s(Poor_Sanitation) + s(Unemployment) + s(Poverty)
104 + s(Timeliness) + te(lon , lat , k = 20) + Year.asFactor,
105 data = TBdata ,
106 family = nb(link = 'log')

```


6.4 Model Summaries and Residual Checks

```

1  # check summary
2  summary(model_poisson)
3
4  Family: poisson
5  Link function: log
6
7  Formula:
8  TB ~ offset(log(Population)) + s(Indigenous) + s(Illiteracy) +
9      s(Urbanisation) + s(Density) + s(Poverty) + s(Poor_Sanitation) +
10     s(Unemployment) + s(Timeliness)
11
12  Parametric coefficients:
13      Estimate Std. Error z value Pr(>|z|)
14 (Intercept) -8.449827   0.004199  -2012   <2e-16 ***
15 ---
16 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
17
18  Approximate significance of smooth terms:
19      edf Ref.df Chi.sq p-value
20 s(Indigenous)      8.961  8.999  569.4 <2e-16 ***
21 s(Illiteracy)      8.989  9.000 2704.0 <2e-16 ***
22 s(Urbanisation)    8.900  8.996 1490.4 <2e-16 ***
23 s(Density)         8.985  9.000 1758.4 <2e-16 ***
24 s(Poverty)         8.956  8.999 1470.2 <2e-16 ***
25 s(Poor_Sanitation) 8.979  9.000 1327.0 <2e-16 ***
26 s(Unemployment)    8.993  9.000 2423.5 <2e-16 ***
27 s(Timeliness)      8.352  8.864  600.7 <2e-16 ***
28 ---
29 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
30
31 R-sq.(adj) = 0.976   Deviance explained = 0.669
32 UBRE = 13.899   Scale est. = 1           n = 1671
33
34 model_poisson$aic
35 34047.36
36
37 # Excerpt from residual check
38 gam.check(model_poisson)
39
40      k`  edf k-index p-value
41 s(Indigenous)    9.00 8.96   0.39 <2e-16 ***
42 s(Illiteracy)    9.00 8.99   0.41 <2e-16 ***
43 s(Urbanisation)  9.00 8.90   0.41 <2e-16 ***
44 s(Density)       9.00 8.98   0.39 <2e-16 ***
45 s(Poverty)       9.00 8.96   0.39 <2e-16 ***
46 s(Poor_Sanitation) 9.00 8.98   0.40 <2e-16 ***
47 s(Unemployment)  9.00 8.99   0.39 <2e-16 ***
48 s(Timeliness)    9.00 8.35   0.43 <2e-16 ***
49 ---
50
51 #check summary
52 summary(model_nb_2)
53
54 Family: Negative Binomial(6.146)
55 Link function: log
56
57 Formula:

```

```

58 TB ~ offset(log(Population)) + s(Indigenous) + s(Urbanisation) +
59   s(Density) + s(Poverty) + s(Poor_Sanitation) + s(Unemployment) +
60   s(Timeliness)
61
62 Parametric coefficients:
63     Estimate Std. Error z value Pr(>|z|)
64 (Intercept) -8.42863    0.01094  -770.6   <2e-16 ***
65 ---
66 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
67
68 Approximate significance of smooth terms:
69           edf Ref.df Chi.sq p-value
70 s(Indigenous)    1.518  1.833  21.13 2.08e-05 ***
71 s(Urbanisation)   6.610  7.752  23.73 0.00167 **
72 s(Density)       4.578  5.667 147.64 < 2e-16 ***
73 s(Poverty)       5.771  6.945  21.36 0.00394 **
74 s(Poor_Sanitation) 6.119  7.293  76.07 < 2e-16 ***
75 s(Unemployment)  5.776  6.977  64.21 < 2e-16 ***
76 s(Timeliness)    4.106  5.103  66.42 < 2e-16 ***
77 ---
78 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
79
80 R-sq.(adj) =  0.86   Deviance explained = 0.439
81 -REML = 7234.9   Scale est. = 1           n = 1671
82
83 model_nb_2$aic
84 14389.56
85
86 # Excerpt from residual check
87 gam.check(model_nb_2)
88
89           k`   edf k-index p-value
90 s(Indigenous)   9.00 1.52    0.49 <2e-16 ***
91 s(Urbanisation) 9.00 6.61    0.50 <2e-16 ***
92 s(Density)      9.00 4.58    0.50 <2e-16 ***
93 s(Poverty)      9.00 5.77    0.49 <2e-16 ***
94 s(Poor_Sanitation) 9.00 6.12    0.50 <2e-16 ***
95 s(Unemployment) 9.00 5.78    0.50 <2e-16 ***
96 s(Timeliness)   9.00 4.11    0.56 <2e-16 ***
97 ---
98
99 # check summary
100 summary(spatial.model.2)
101
102 Family: Negative Binomial(12.246)
103 Link function: log
104
105 Formula:
106 TB ~ offset(log(Population)) + s(Indigenous) + s(Urbanisation) +
107   s(Density) + s(Poor_Sanitation) + s(Unemployment) + s(Poverty) +
108   s(Timeliness) + te(lon, lat, k = 20)
109
110 Parametric coefficients:
111     Estimate Std. Error z value Pr(>|z|)
112 (Intercept) -8.467186    0.008485  -997.9   <2e-16 ***
113 ---
114 Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
115
116 Approximate significance of smooth terms:
117           edf Ref.df Chi.sq p-value
118 s(Indigenous)    3.700  4.346  19.53 0.000922 ***
119 s(Urbanisation)   5.188  6.221  52.90 < 2e-16 ***
120 s(Density)       4.107  5.012  38.40 1.58e-06 ***

```

```

121 s(Poor_Sanitation) 5.367 6.412 27.55 0.000174 ***
122 s(Unemployment) 4.132 5.125 79.61 < 2e-16 ***
123 s(Poverty) 6.716 7.729 42.69 < 2e-16 ***
124 s(Timeliness) 2.445 3.053 46.59 < 2e-16 ***
125 te(lon,lat) 139.341 174.137 1088.66 < 2e-16 ***
126 ---
127 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
128
129 R-sq.(adj) = 0.926 Deviance explained = 0.699
130 -REML = 6987.8 Scale est. = 1 n = 1671
131
132 spatial.model.2$aic
133 13650.8
134
135 #Excerpt from residual check
136 gam.check(spatial.model.2)
137
138      k`      edf k-index p-value
139 s(Indigenous)      9.00   3.70   0.63 <2e-16 ***
140 s(Urbanisation)      9.00   5.19   0.61 <2e-16 ***
141 s(Density)          9.00   4.11   0.63 <2e-16 ***
142 s(Poor_Sanitation)  9.00   5.37   0.61 <2e-16 ***
143 s(Unemployment)      9.00   4.13   0.62 <2e-16 ***
144 s(Poverty)          9.00   6.72   0.61 <2e-16 ***
145 s(Timeliness)       9.00   2.45   0.66 <2e-16 ***
146 te(lon,lat)        399.00 139.34   0.65 <2e-16 ***
147 ---
148
149 # check summary
150 summary(spatio.temporal.model.2)
151
152 Family: Negative Binomial(12.299)
153 Link function: log
154
155 Formula:
156 TB ~ offset(log(Population)) + s(Indigenous) + s(Urbanisation) +
157      s(Density) + s(Poor_Sanitation) + s(Unemployment) + s(Poverty) +
158      s(Timeliness) + te(lon, lat, k = 20) + Year.asFactor
159
160 Parametric coefficients:
161      Estimate Std. Error z value Pr(>|z|)
162 (Intercept) -8.4532889 0.0144206 -586.197 <2e-16 ***
163 Year.asFactor2013 -0.0005816 0.0201595 -0.029 0.977
164 Year.asFactor2014 -0.0417054 0.0202005 -2.065 0.039 *
165 ---
166 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
167
168 Approximate significance of smooth terms:
169      edf Ref.df Chi.sq p-value
170 s(Indigenous)      3.702 4.347 19.56 0.000912 ***
171 s(Urbanisation)      5.197 6.230 53.05 < 2e-16 ***
172 s(Density)          4.107 5.011 38.45 1.89e-06 ***
173 s(Poor_Sanitation)  5.374 6.418 27.61 0.000170 ***
174 s(Unemployment)      4.145 5.140 80.03 < 2e-16 ***
175 s(Poverty)          6.722 7.734 42.72 < 2e-16 ***
176 s(Timeliness)       2.460 3.070 46.59 < 2e-16 ***
177 te(lon,lat)        139.707 174.516 1093.31 < 2e-16 ***
178 ---
179 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
180
181 R-sq.(adj) = 0.926 Deviance explained = 0.701
182 -REML = 6991.1 Scale est. = 1 n = 1671
183

```

```

184 spatio.temporal.model.2$aic
185 13647.93
186
187 #Excerpt from residual check
188 gam.check(spatio.temporal.model.2)
189
190          k`      edf k-index p-value
191 s(Indigenous)    9.00  3.70   0.63 <2e-16 ***
192 s(Urbanisation)  9.00  5.20   0.60 <2e-16 ***
193 s(Density)       9.00  4.11   0.62 <2e-16 ***
194 s(Poor_Sanitation) 9.00  5.37   0.61 <2e-16 ***
195 s(Unemployment)  9.00  4.15   0.61 <2e-16 ***
196 s(Poverty)       9.00  6.72   0.61 <2e-16 ***
197 s(Timeliness)    9.00  2.46   0.66 <2e-16 ***
198 te(lon,lat)      399.00 139.71  0.64 <2e-16 ***
199 ---

```