Mapping Murder

I. Summary

In order to aid in the investigation of serial criminals, we use four schemes to generate geographical profiles, which show the possible locations of the criminal's home (or anchor point). Different schemes are implemented with different decay functions which describe the criminal's spatial behavior. Score function is used to evaluate the possibilities at every point. And the sum of scores indicate the probability of being the anchor point.

After geographical profiling, a prediction about future crime locations and time is made. Firstly, one of the four schemes may be used to generate a probability surface. Then, the analysis about location patterns rectifies the values on the probability surface, producing a final prediction on future crime locations. Finally, a prediction on time patterns is given, based on the analysis on the time intervals.

Four typical models are built and assessed on their reliability and sensitivity. . Predictions are verified by data. Further analysis gives recommendations on the choice of models. The case analyzed in this article is 'The Yorkshire Ripper'

We conclude from the analysis that,

1. Our geographical profiles generated by four schemes accurately narrow the search area to where the anchor point (home) of criminal actually is.
2. The prediction of location is verified by historical data, but with deviations. The analysis of time intervals provides some intuitive estimations.

II. Executive Summary

Executive Summary to the Police – A Search Guide for Police

1. Assumptions for the model
   (1) The serial crimes are committed by a single criminal.
   (2) There exists only one anchor point (home, work place, etc.) for the criminal and he/she is physically and emotionally related to this anchor point. He/she is a 'marauder' type criminal, instead of a transient criminal. He/she usually commits crimes within a distance from anchor point.
   (3) For most cases, there exists a buffer zone around the anchor point in which the criminal is unlikely to commit a crime.
   (4) Limited or complete information on time and location is collected.
   (5) In the present stage, the influence of race, sex, age, and other demographic and geographical factors are excluded.
   (6) The analysis will be more accurate if empirical database exists in the area where the crimes commence, such as the mean buffer zone radius, etc.

2. From known to unknown with time and location – decision making map
   Prediction function: $P(x,m,t) = D(d(x,m))$

Model name	GM	EPM	LNDM	RM
Theory behind	Geometry	Physics	Statistics	Rossmo's
Decay function ~ Probability distribution	Uniform	-	Lognormal	Rossmo's
Exact location known (accurate to town)	√	√	-	√
Sample area size	Small	Large	-	-
Lease Number of cases	>3	>2	>10	>10
Regular sites distribution	-	-	√	√
Empirical Buffer Zone size	√	√	-	-
Data Output	BZ	AP	BZ	BZ
Distance Calculation Method	E	E	E	M

*BZ: Area inside Buffer Zone & Probability distribution *AP: Exact Anchor Point

*E: Euclidean Distance *M: Manhattan distance

3. Overview performance of prediction based on four models
   (1) **Geometric Model (GM)** generates a most probable searching area with the input of crime locations and estimated radius based on the investigation and experience. This model is valid for those offenders that would only commit crimes within a region near their residence and more accurate for a small region.
   (2) **Log Normal Decay Model (LNDM)** generates a most probable searching area with the input of crime locations only. The parameters of the distribution are

obtained from the input crime locations so that it is free from input empirical parameters. For this reason, this model is the least sensitive to the false crime sites information. This model is valid for common serial murder offenders that would commit crimes away from residence but not too far.

(3) **Rigel Model (RM)** generates a most probable searching area with the input of crime locations and empirical buffer zone radius based on current evidence. This model is valid for common serial murder offenders that would commit crimes away from residence but not too far and most probably at a distance which are implemented by an abrupt distance decay function.

(4) **Efficient Path Model (EPM)** generates a most probable anchor point with the input of crime locations only. This model is valid for the offender that tends to take the shortest path back home after committing a crime.

4. More known reveal more truth

Prediction function: $P(x,m,t) = D(d(x,m)) \cdot G(x) \cdot T(t) \cdot PT(x)$

(1) $G(x)$ can model the geographical and demographical distribution around the crime scene, you can empirically choose the appropriate models according to the local criminal database.

(2) $T(t)$ can model the 'Periodic crime', based on the particular criminal's behavior.

(3) $PT(x)$ is the direction factor which intensifies the probability of a predicted moving direction based on the particular criminal's previous movement.

Suggestion: As more and more factors are taken into consideration, the prediction should be much and much closer to the next crime scene; however, when using models in reality, human judges are always weighed heaviest during a prediction.

5. Function list

Model Name	Decay Function
Geometric Model (GM)	$D(d(x,m))= C \quad d(x,m)<B$ $D(d(x,m))= 0 \quad d(x,m)>B$
Efficient Path Model (EPM)	$D(d(x,m)) = -m$
Lognormal Distribution Model (LNDM)	$D(x;\mu,\sigma)=\frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}, x>0$
Rigel Model (RM)	$D\left(d(m_i,m_n)\right) = \frac{1}{(\lvert x_i-x_n\rvert+\lvert y_i-y_n\rvert)^f} \quad d(x,m)<B$ $D\left(d(m_i,m_n)\right) = \frac{1-\varphi}{(2B-\lvert x_i-x_n\rvert-\lvert y_i-y_n\rvert)^g} \quad d(x,m)>B$

III. Key Assumptions

- The criminal is a marauder serial killer and there exists one and only one anchor point.
- There exists a buffer zone around the anchor point in which the killer is not likely to commit a crime.
- Serial killers are not likely to commit crimes near their homes, or travel far from their anchor point.
- Victims are equally possible despite their sex, age or race.
- Only locations are concerned in geographical profiling. Predictions are primarily based on criminal locations and time.
- Latitude and the longitude of the town are used to locate the crime sites.

IV. Definitions

- Buffer zone
- Sample area: The minimum rectangle containing all the crime sites, denoted by S.
- Anchor point, denoted by P(m1, m2), or m=(m1,m2).
- Anchor point area: the area with the highest possibility that the anchor points will lie, denoted by A.
- Number of crime scenes: N
- Criminal cite: accurate to the longitude and latitude of the town of the crime scene, denoted by $c_i, 1 \leq i \leq N$, or ci=(x1, x2).
- Criminal cite area: area of the circle around the criminal cite with radius equal to the assumed buffer zone radius.
- Displacement: Euclidean distance between two sites y=(y1,y2) and z=(z1,z2) is

  $$r(y,z) = \sqrt[2]{(y_1 - z_1)^2 + (y_2 - z_2)^2}$$

- Distance: Manhattan distance between y=(y1,y2) and z=(z1,z2) is $r(y,z) = |y_1 - z_1| + |y_2 - z_2|$.
- Decay function: models the possibility of the crime at different location, with the highest probability at the point on the buffer belt, denoted by D(x,m).
- Hit score: The probability that y being an anchor point. Hit score function: $S(\mathbf{m}) = \sum_{i=1}^{N} D(\mathbf{c}_i, \mathbf{m})$.
- The actual home location is found to be (88,75) in the 100*100 pixel mapping.

V. Geographical Profiling

5.1 Geometric Model(GM)

5.1.1 *Model Derivation*

(1) Assumption: The criminal tends to commit serial crimes within a buffer zone with the same possibility at any point within a constant radius, which is an empirically determined constant.

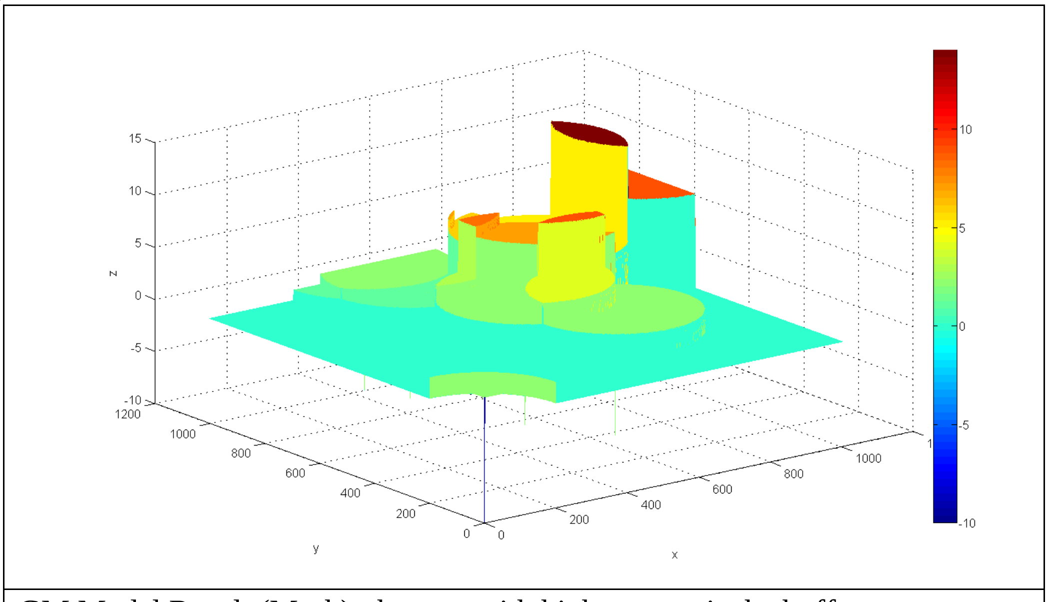
(2) Insight: Vein gram

(3) Arithmetic: Circles centered at each crime sites with radius of buffer zone are plotted on the visual map one by one and overlap on the top of each other. The probability of anchor point inside the circle is p while outside the circle 1-p. By superimposing the probability of each circle, the resultant probability of map is generated. The anchor point area will be the overlap of circles whose center is the criminal cite and radius the buffer zone is the place most frequently passed by the murder.

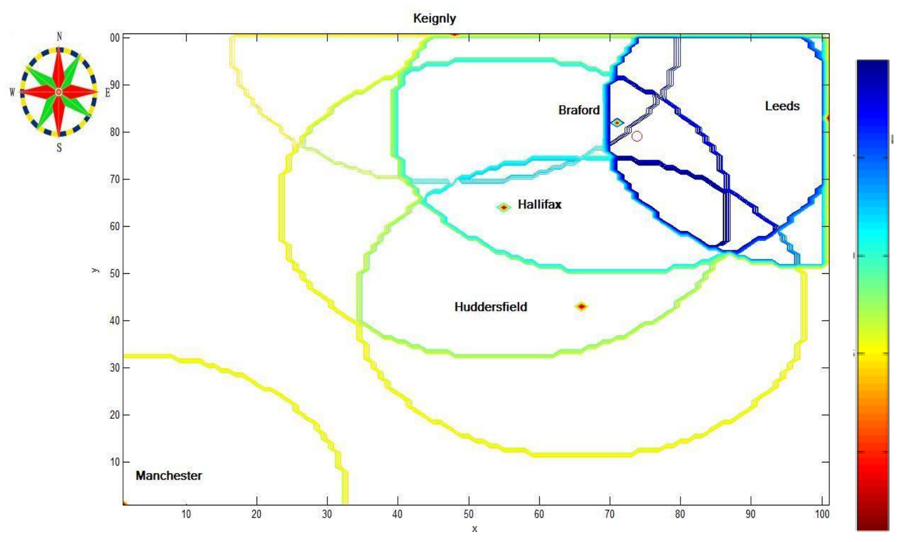
(4) Mathematical representation: $A = \cap_{i=1}^{N} C_i$

(5) Technique: Using MATLAB, we plot the criminal cites circular area and stress the overlapping area with deeper color.

(6) Result:



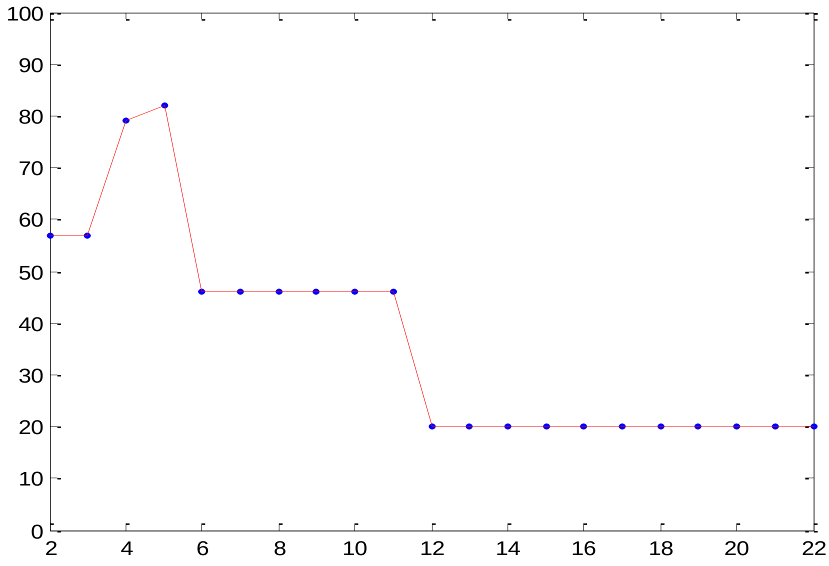
GM Model Result (Mesh): the area with higher score is the buffer zone



GM Model Result (Contour): The area bounded with 2 blue circles is the buffer zone

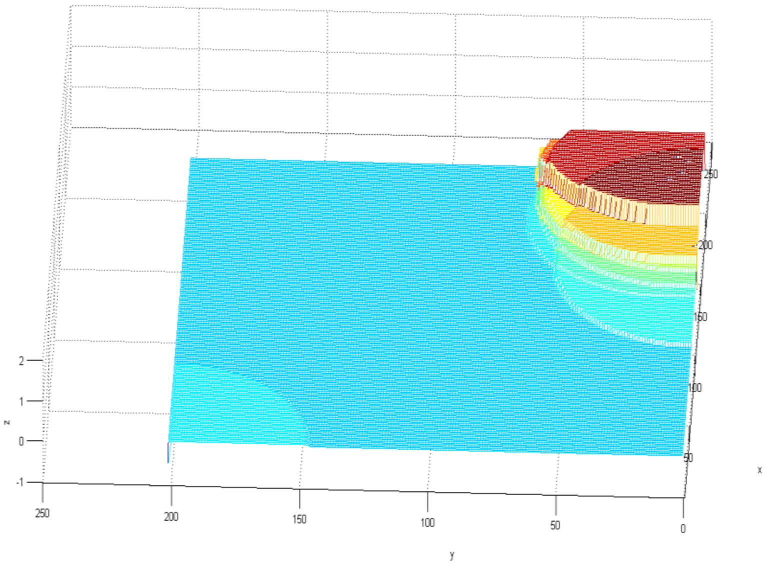
5.1.2 *Model Analysis*

1) Validity: The actual point lies in the predicted buffer zone.
2) Reliability:
   - ✓ This model assumes that inside a criminal area the possibility of committing a crime is the same, which is not the case in reality. From psychological point of view, criminal is unlikely to commit a crime near his residence; therefore this model only applies to those with small buffer zone radius.



   - ✓ The more the points, the accurate the result. The above graph plots the distance between actual anchor point and the most probable anchor point versus the number of known crime sites. The more sites are available, the more precise of the anchor point estimation.

- ✓ It is sensitive to change of one site location. If one false crime site (59.799637,-3.54911) is "mixed" into the mapping algorithm, the probability map is changed to the figure below and the error of the anchor points becomes 137, which is greater than the previous error. The choice of encounter site and dispose site also differ the deviation.

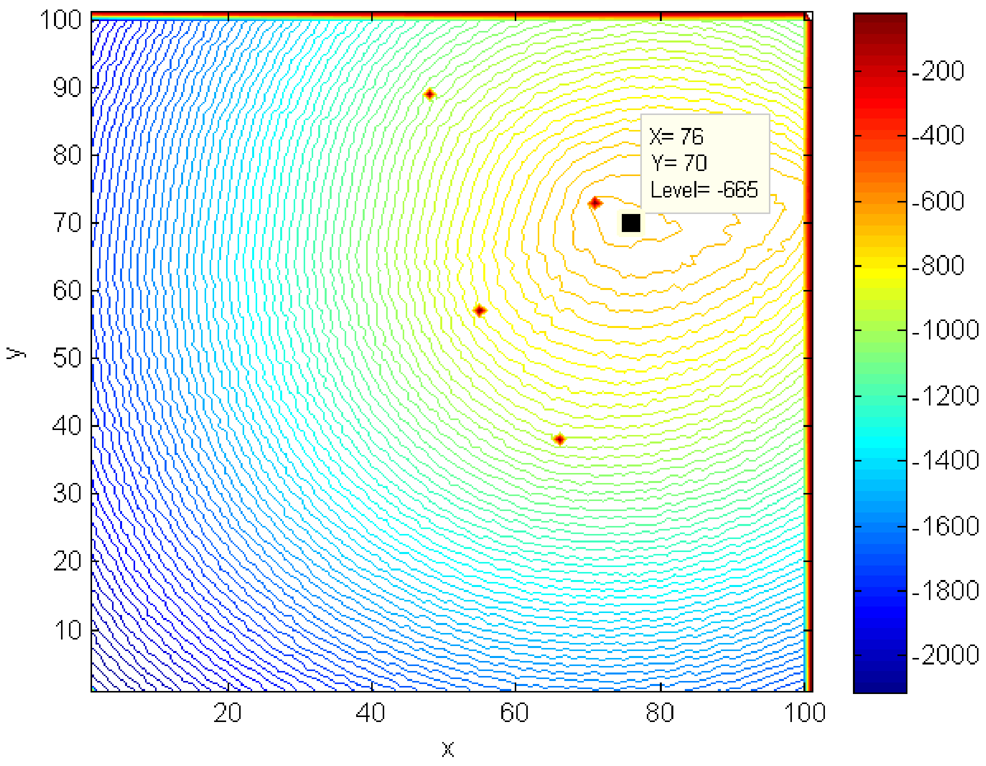


3) Utility
   This model can be applied to serial crimes in a relatively small area, with small empirically determined buffer zone radius.

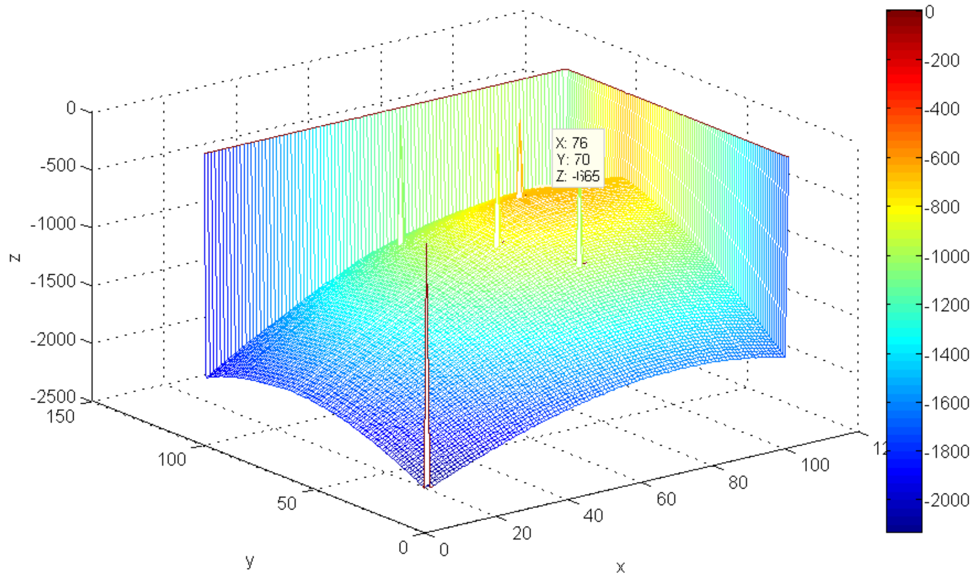
5.2 Efficient Path Model (EPM)

5.2.1 *Model Derivation*

(1) Assumption: For the criminal, efficiency means always taking the shortest path from and to the anchor point.
(2) Arithmetic: The anchor point will be the point with the minimum distance to all the crime cites.
(3) Insight: Central of gravity.
(4) Mathematical representation: C
(5) Technique: Using MATLAB, we calculate the sum of the distance from each point in the sample area to the crime cites, then we find the minimum distance, and the corresponding point is the anchor point.
(6) Result: (76,70)



EPM Model Result (Contour): exact anchor point is given, which is (76,70)



EPM Model Result (Mesh): exact anchor point is given, which is (76,70)

5.2.2 *Model Analysis*

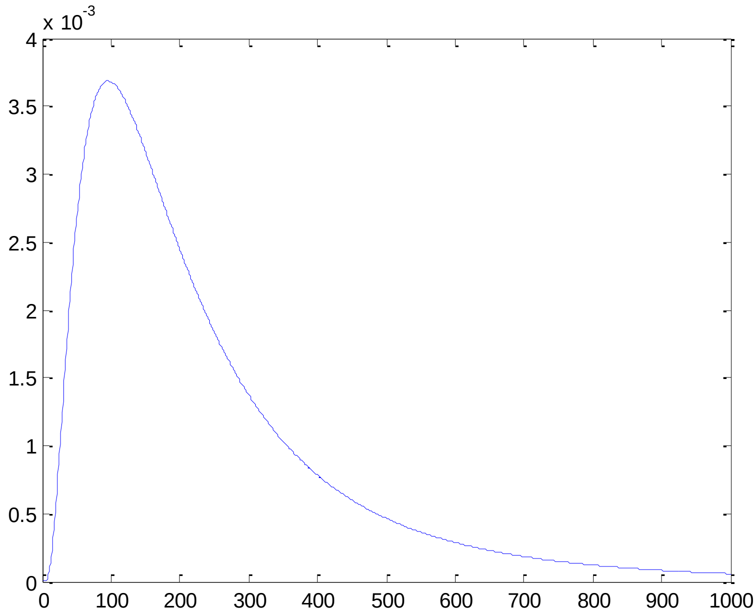
1) Validity: The predicted anchor point differs from the actual point by 13, which is an acceptable error in the virtual map.
2) Reliability:
   This model is reliable if, once the offender commits a crime, he will attempt to go back home as soon as possible. If the offenders avoid committing crimes at some certain places not uniformly distributed through the sample area, this simple model is not reliable.
3) Utility: This model is suitable for the serial crime in a relative large area, in which case the criminal is likely to go back home as soon as he commits the crime because he may not familiar with the new area. Also, in a larger area, we can use the Euclidean distance instead of the Manhattan distance in large scale.

5.3 Log Normal Decay Model (LNDM)

5.3.1 *Model Derivation*

(1) Assumption:
   1) There exists a buffer zone around the anchor point.
   2) There is a decay function.
   3) The presumed anchor point is the central of gravity of the crime cites.
      i. N>10 for statistical analysis

(2) Technique:
   1) Find the probability of crime for different distance from presumed anchor point.



2)Find a prior probability distribution that model the pattern of the probability of crime, which appears to be a log-normal distribution.

3)Take the log-normal probability distribution function as the decay function.

4)Find the anchor point by calculating the hit score of each possible point in D.

(3) Arithmetic and Mathematical representation:

1)$D \sim \text{Lognormal}(x; \mu, \sigma)$

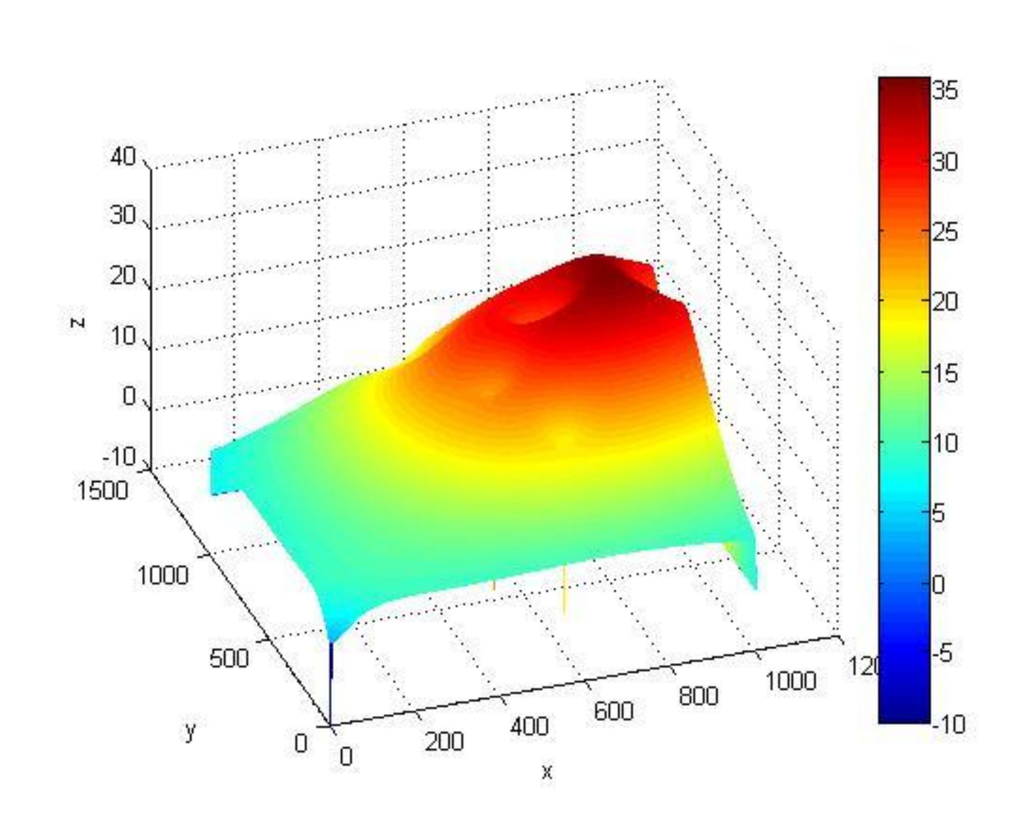
2)Estimate parameters using maximum likelihood

$$\mu = \frac{\sum_{i=1}^{N} \ln r_i}{N}, \quad \sigma^2 = \frac{\sum_{i=1}^{N} (\ln x_i - \mu)^2}{N}$$

3)$D(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}, x > 0$

4)Calculate $S(\mathbf{m}) = \sum_{i=1}^{N} D(\mathbf{c}_i, \mathbf{m})$ and find **m**.

(4) Result:

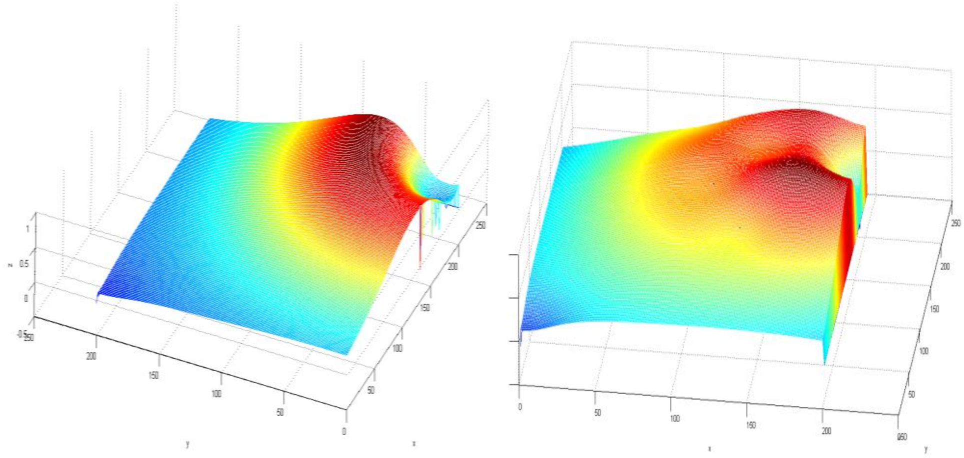


LNDM Model Result: Area with high score indicates the buffer zone

5.3.2 *Model Analysis*

1) Validity: The buffer zone of x∈[900,100] and y∈[1100,1300] contain the actual anchor point (880, 1125).
2) Reliability:
   1) Distances are analyzed statistically and the discrete points are approximated by a probability distribution function; different case may follow different pattern. The mean value and variance of lognormal function is dependent on the crime sites and calculated from the crime locations without adopting any empirical data, which is easier to calculate.

2) **It is sensitive to change of one site location.** If one false crime site location is input to this model, the probability map is shown as below in contrast with correct map.



As observed in the above figures, the jeopardy surface perturbs less than that predicted by other models, indicating better performance.

3) Utility: This model can be applied to crimes with distances with a regular distribution.

5.4 Rigel Model (RM)

5.4.1 *Model Derivation*

(1) Assumption:

1. There exists a buffer zone around the anchor point.
2. There is a decay function.
3. The decay function applies to the Rossmo's method.
4. Criminal is not likely to commit a crime in the buffer zone, and less likely to commit a crime further from the anchor point outside the buffer belt.
5. N>10 for statistical analysis

(2) Arithmetic and Mathematical representation:

The hit score of point P(i,j) is

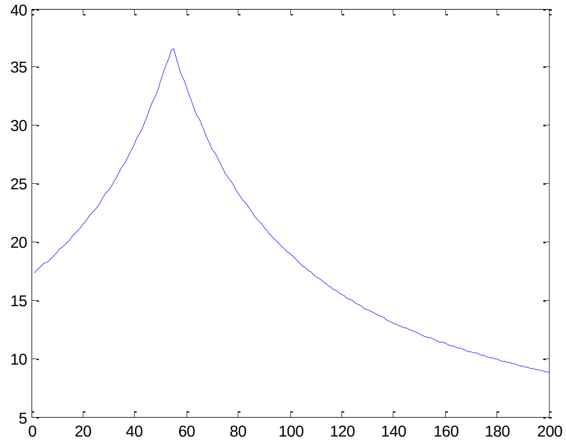
$$P_{ij} = k\sum_{n=1}^{N} \frac{\varphi}{(|x_i - x_n| + |y_i - y_n|)^f} + \frac{1-\varphi}{(2B - |x_i - x_n| - |y_i - y_n|)^g}$$

$\varphi = 1$ when (i,j) is in the buffer zone and $\varphi = 0$ outside.

f and g are empirical exponents, here f=g=1.2 for crime.

k is a constant computed so that P_{ij} serves to be a probability distribution

function, i.e. $\iint_0^\infty P_{ij} dx_i dy_i = 1$

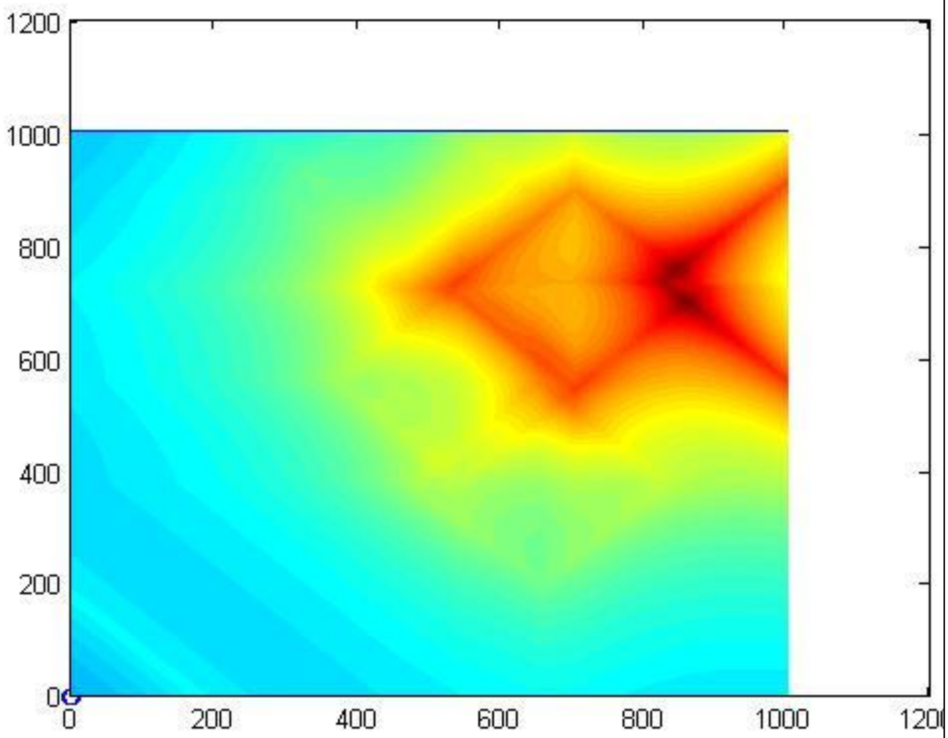


(3) Explanation of Rossmo's method:

There are two parts in the decay function:

1. Part one is considered when the criminal is in the buffer zone. The closer he gets to the anchor point, the less likely that he will commit a crime.
2. Part two is considered when the criminal is outside the buffer zone. The further he gets away from the anchor point, the less likely that he will commit a crime.

(4) Result:



RM Model Result: Area with high score indicates the buffer zone

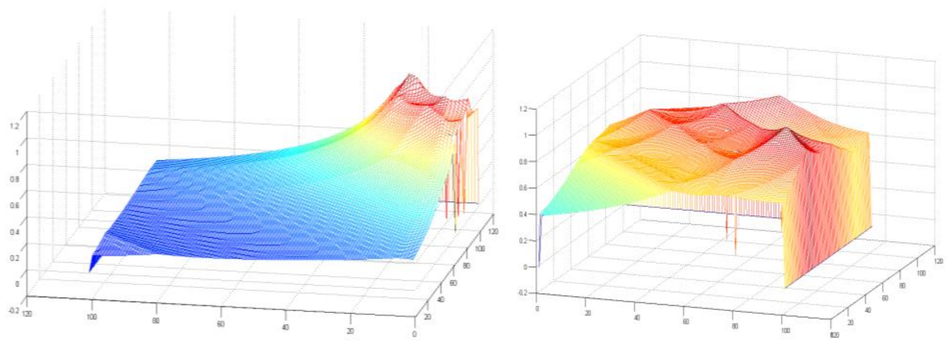
5.4.2 *Model Analysis*

1) Validity: The buffer zone of x∈[850,950] and y∈[650,800] contain the anchor point (880, 750)

2) Reliability:

The key of this algorithm is decay function which models the preference of distance choosing for most offenders. However, different person has different preference and this peculiarity (including the traffic tools, personal characteristics, and awareness on anti-investigation and psychological status at the time of committing crimes) determines the value of the buffer zone radius B in the formula of this model. Even for the same person, the above factors may vary over time. Thus it is difficult to figure out the benchmark for the buffer zone. Empirically, the value of radius B is equal to the average of the distance between two chronological crime sites and is assumed to be constant.

If one false crime site information is input to this model, the probability map is shown as below in contrast with correct map. The input crime location should be verified and investigated carefully and substantiate evidence should be discovered to verify the crime location and the newly discovered case is related to the previous cases. Otherwise, the false information will drive the location of search area away.



3) Utility:

The core part of this model is distance decay function and hit score probability. The decay function is applicable to those serial crimes with distance distribution estimated by Rossmos method.

VI. Prediction

6.1 Location Pattern

6.1.1 *Model Derivation*

Formula

$$P(x,m,t) = D(d(x,m)) \cdot TP(x)\ G(x) \cdot T(t)$$

x : the location of a specific point
m: the location of the anchor point (derived from the previous part)
t: the time coefficient
P(x,m,t) predicts the probability that the next crime happens at a specific location x.
D(d(x,m)) describes the relationship between the probability of crime and the distance from the anchor point.
TP(x) shows that the travel pattern of the criminal at x will affect the probability.
G(x) evaluates the demographical and geographical factors at x.
T(t) evaluates the influence of time

Additional assumptions

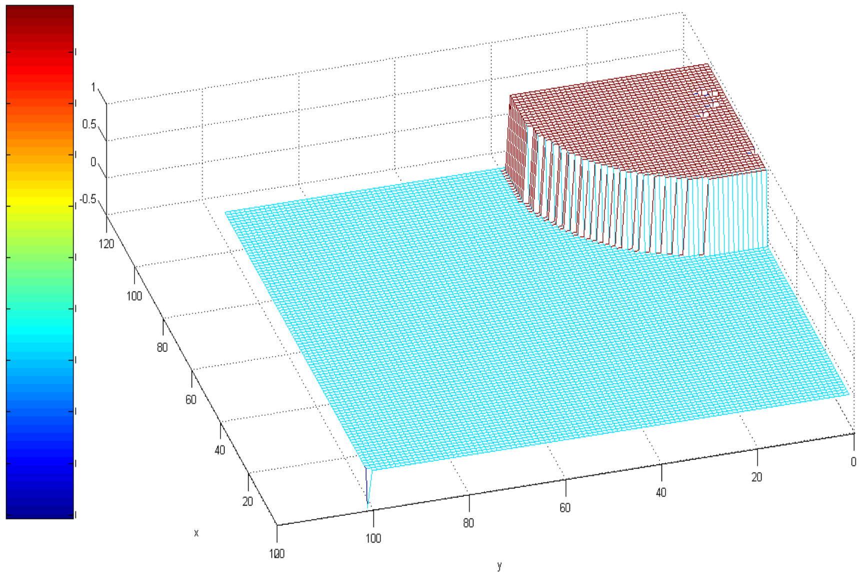
(1) G(x)=1 during our analysis for simplicity. This is discussed in 6.3 Other Factors.
(2) T(t) is determined by historical data. Lacking of relevant data, we take it to be the probability that when time interval between chronological crimes equals to t.

Basically t $\propto \frac{1}{d(m,x)}$, T(t) $\propto \frac{1}{D(d(m,x))}$, for the same decay function, T(t) can be assumed the same. Note that T(t) will vary if G(x) changes, according to assumption (1), T(t) can be hold constant in this case, for simplification let T(t)=0.5.

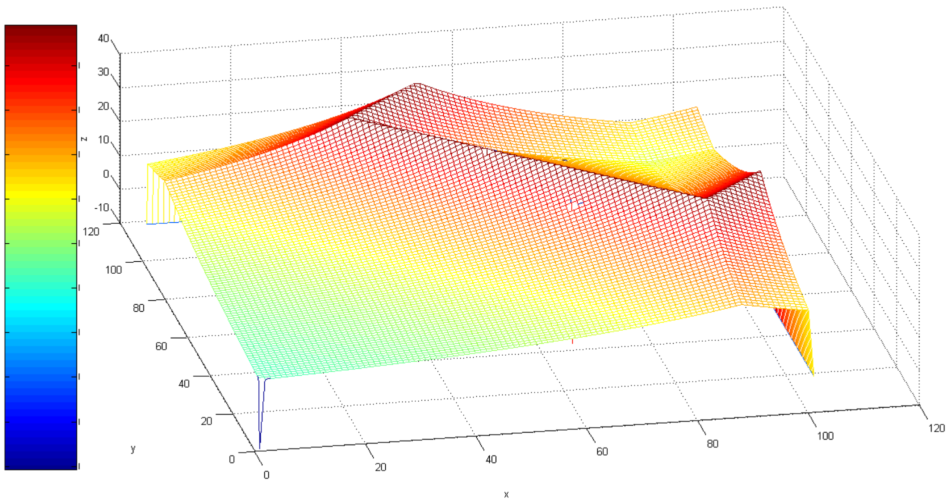
In our analysis, P(x,m,t) can be evaluated using $P(x,m,t) = D(d(x,m)) \cdot TP(x)$, after evaluating the Jeopardy Surface D(d(x,m)) and Travel Pattern TP(x).

6.1.2 *Jeopardy Surface*

Jeopardy Surface is described by (xx,xy,D(d(x,m))). The score function is also used in calculating D(d(x,m)). The crimes are more likely to happen in the area with higher score of D(d(x,m)).



If the Geometric Model (GM) is used, as shown above, the next crime is most likely to be located within B miles from the anchor point.

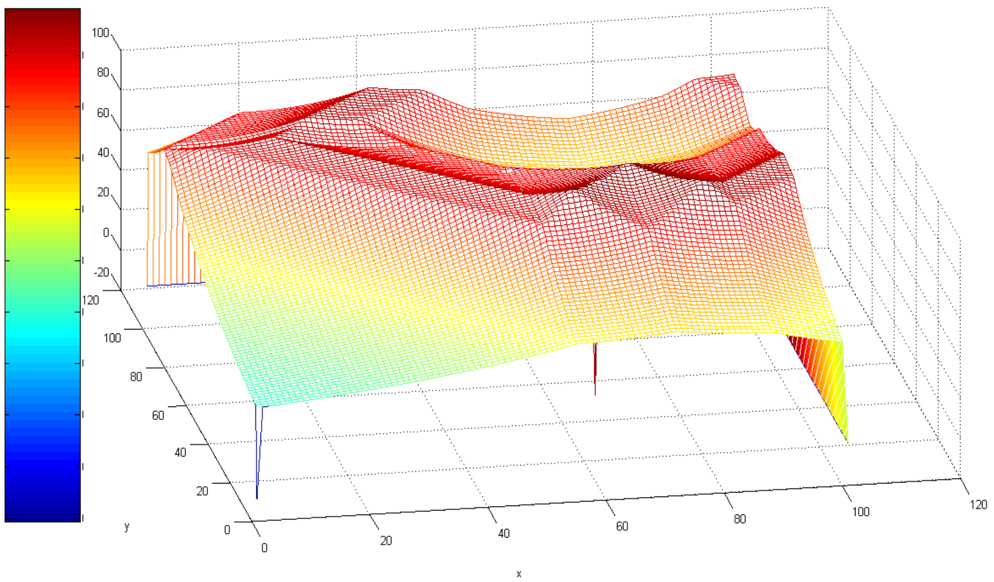


If the Rigel Model is applied, as shown in the above mesh plot, the most probable crime locations fall on a belt around the buffer zone, marked in deep red.

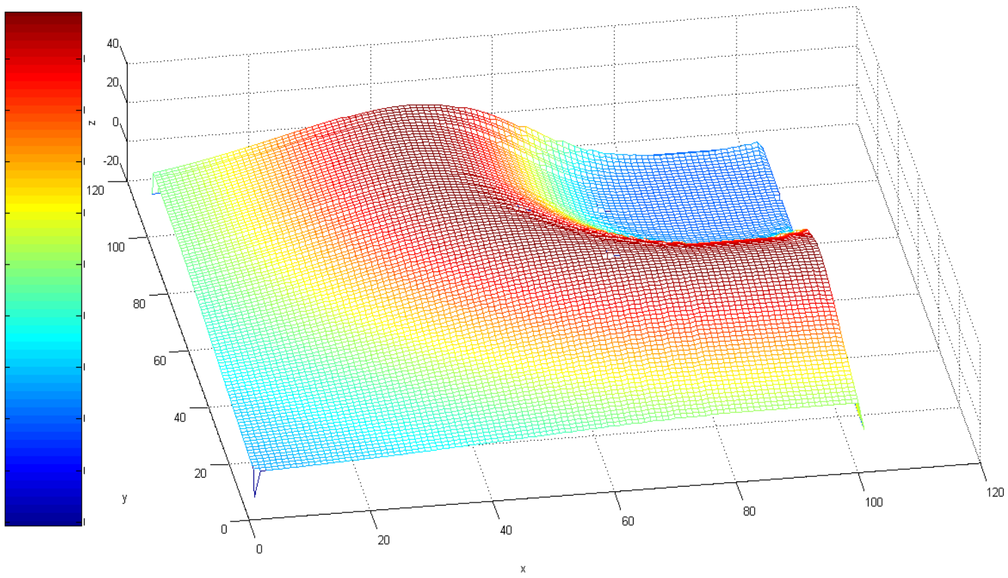
If multiple possible anchor points are derived during geographical profiling,

$$D(d(x, m)) = \sum_{k=0}^{n} J(x, m_k)$$

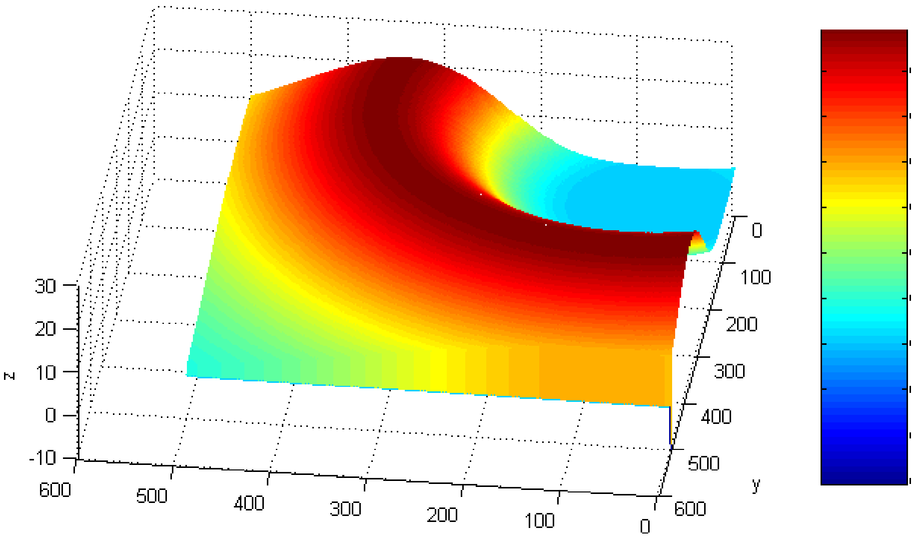
If a closed anchor area is used, it can be viewed as a number of anchor points after discretization. The graph below shows the Rigel Plot with three anchor points derived from the geographical profiling. Therefore, Jeopardy Surface can be plotted even if anchor point is not unique.



The jeopardy surface of Log-Normal Decay Model is also shown below. Note that this surface clearly show that criminals tend to avoid the locations near their anchor point and those that are too far away.



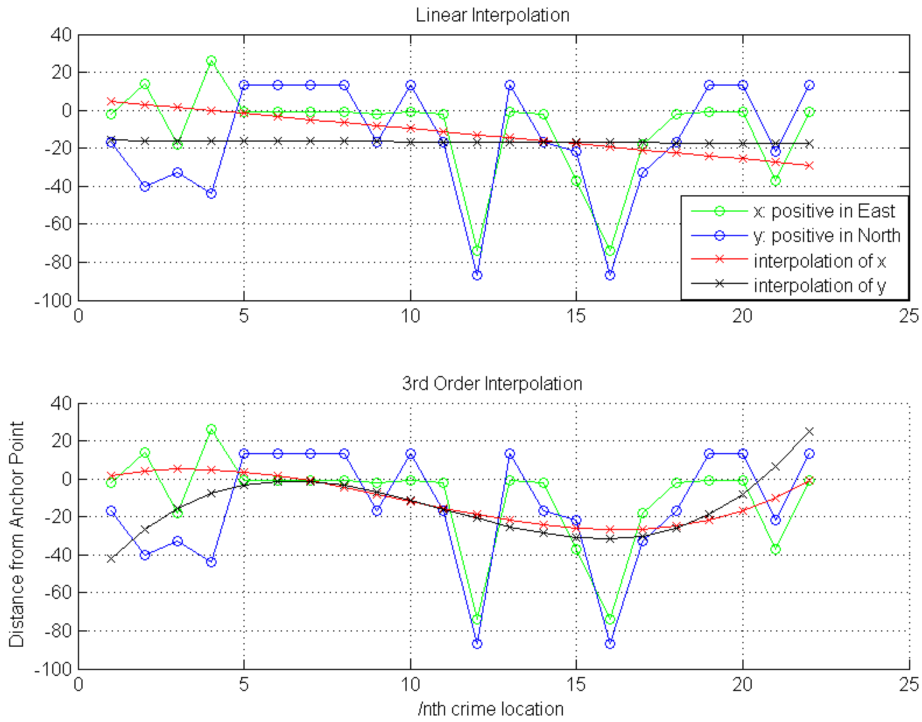
A comparison can be made if there are three anchor points in the below Log-Normal Decay Model.



6.1.3 *Crime Location – Anchor Point Pattern*

In order to reveal the travel patterns behind the movements, the distances between all crime locations and the anchor point are sorted chronologically, and plotted independently in longitude and latitude, as shown below. x is positive in east and y in north. Denote the points by xi (in green line), yi (in blue line).

After that, we use two 3rd order polynomials and two linear functions to interpolate all the points, to predict the trends of movements in x and y direction:
f1(n): nth element on the linear interpolation of xi
g1(n): nth element on the linear interpolation of yi
f3(n): nth element on the 3rd order interpolation of xi
g3(n): nth element on the 3rd order interpolation of yi



It can be observed from the graph that xi and yi generally fluctuate around the interpolation curves. It is reasonable to estimate that

$$\min(f1(n),f3(n)) \leqslant xn+1 \leqslant \max(f1(n),f3(n))$$
$$\min(g1(n),g3(n)) \leqslant yn+1 \leqslant \max(g1(n),g3(n))$$

we can let Travel Pattern Function TP(x) = k for all (xx,xy) satisfying the conditions and TP(x) = 1 elsewhere, k>1 indicating that at x the probability of crime is greater.

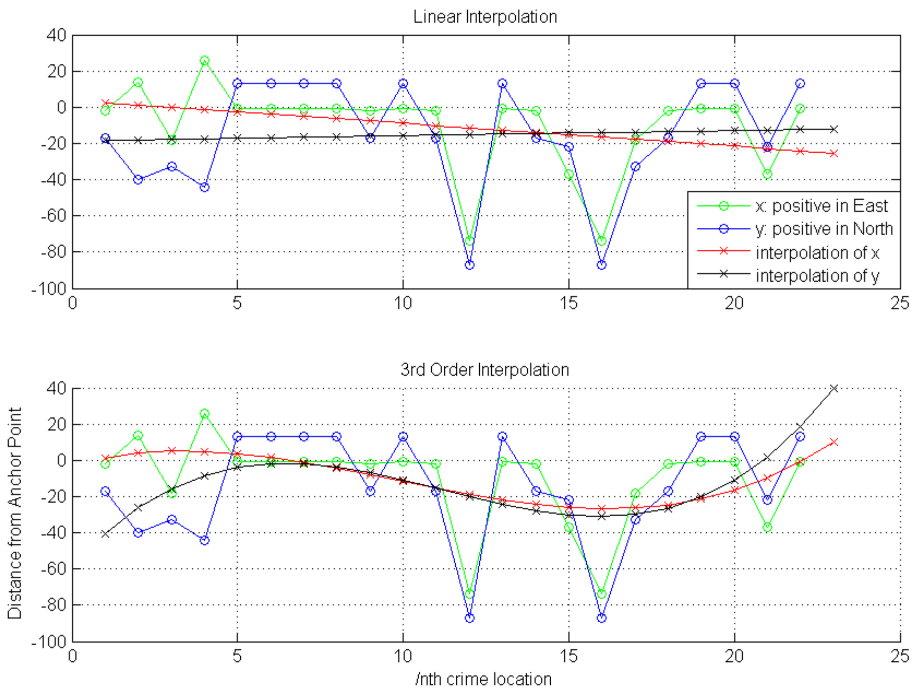
Another approach may take the TP(x) = k for all (xx,xy) lies in a circle centered at $\left(\frac{f1(n)+f3(n)}{2}, \frac{g1(n)+g3(n)}{2}\right)$ with radius = $\frac{\sqrt{(f1(n)-f3(n))^2+(g1(n)-g3(n))^2}}{2}$. We use this TP(x) in calculation, since Euclidean distance is more commonly used than Manhattan distance.

From mathematical point of view, there exists a line dividing the curve into two parts, so that the area of the upper part is equal to that of the lower part, thus the possibilities are the same for xn+1 to go above or below the interpolation curves.

Only lower order interpolations are implemented because a higher degree of the polynomials, will have more drastic perturbations at two ends, and lower reliability in predicting the trend of xi, yi.

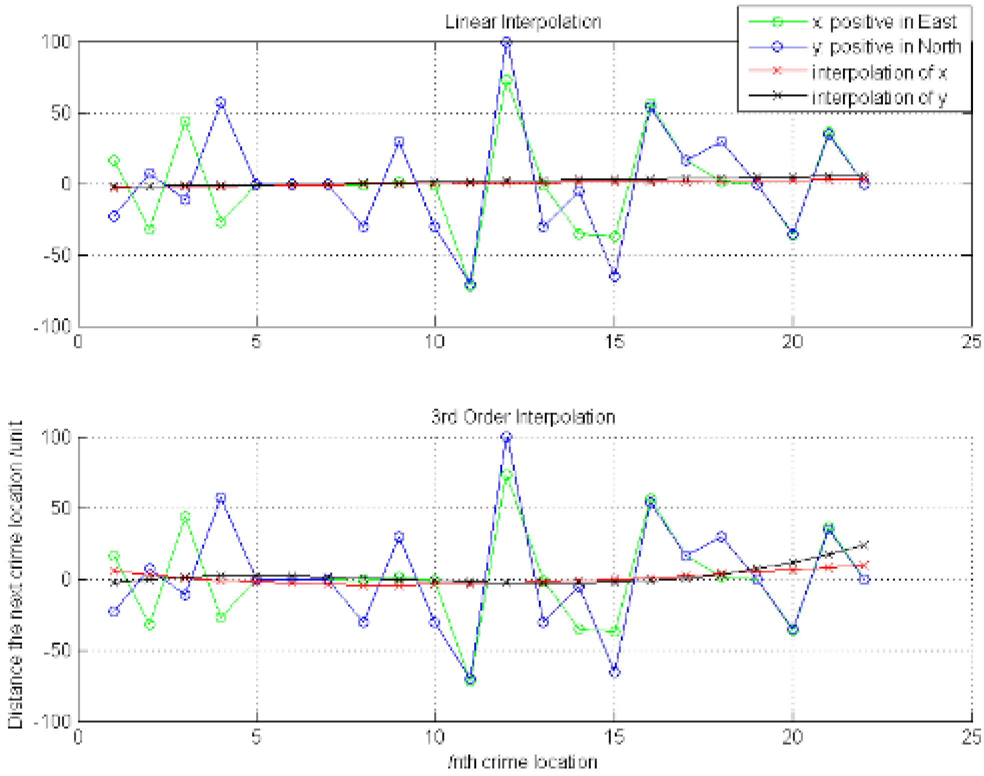
Validity

To prove that our estimation of xn+1, yn+1 is valid, the graph below uses N-1 points to predict the nth crime locations, which can be verified by the actual coordinates of x,y. The results show that the two functions predict the movement of x,y with tolerable deviations.

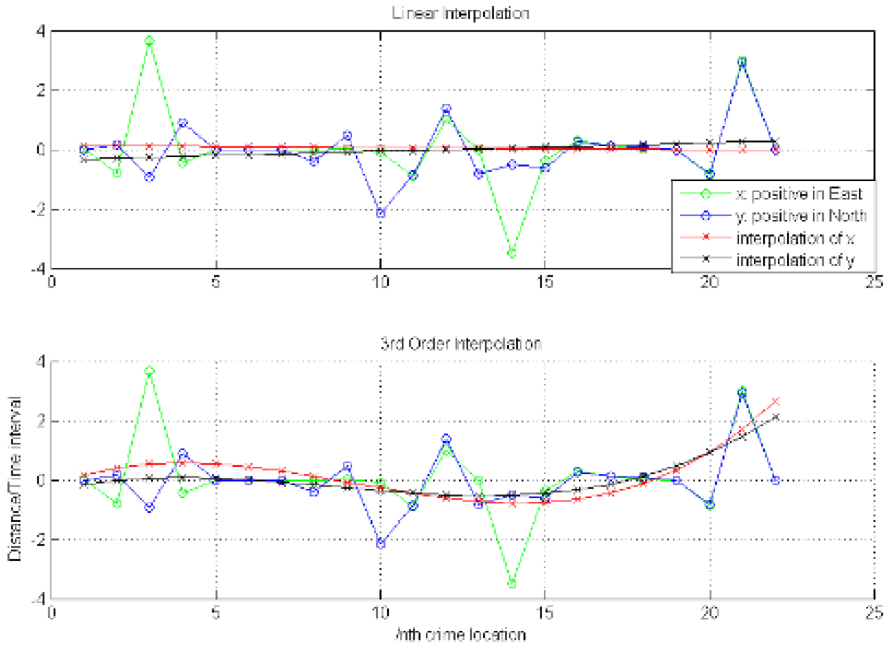


6.1.4 *Crime Location – Crime Location Pattern*

Travel pattern: view from chronological site



(Graph 31 above) The distances between two chorological crime locations, and the interpolations

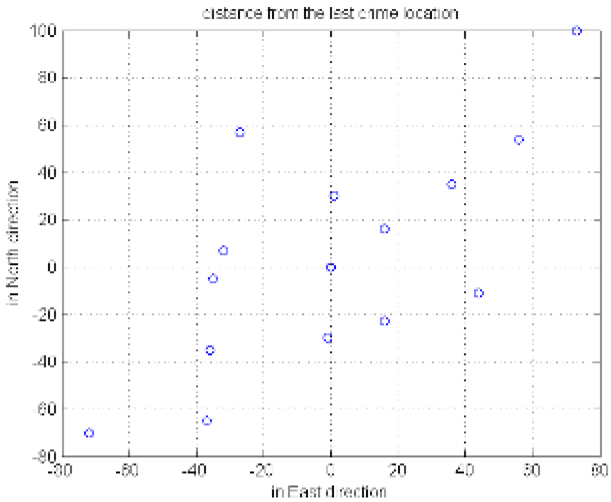


This again shows that the criminal tends to go to the other direction for new crimes, and hence provide a firm foundation that Yorkshire Ripper is a 'local hunter' instead of a 'traveler'. Thus we can use these models to predict the anchor points.

(Graph 32 above) The distances / time interval

6.1.5 *x-y Correlation Analysis*

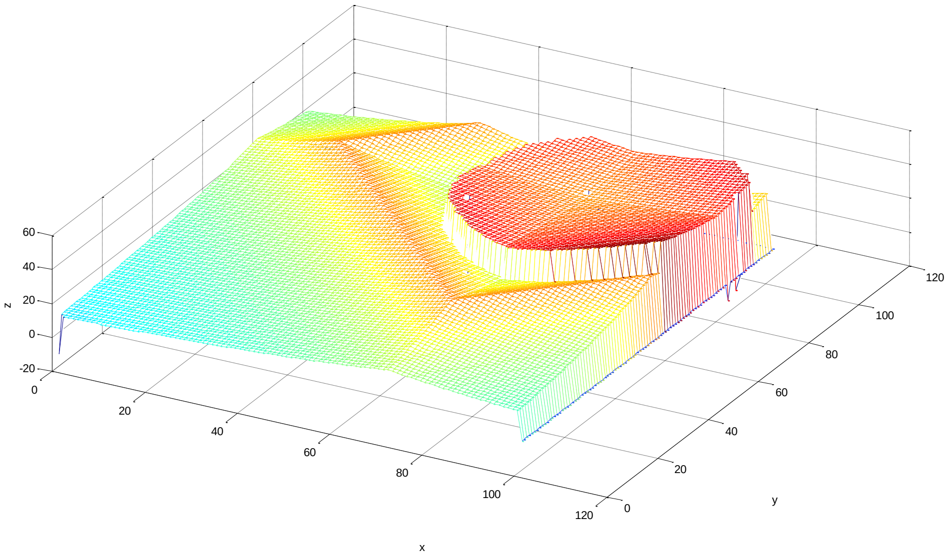
Displacement in x and y direction are independent of each other, according to the statistics.



(Graph 33) The y movements vs. x movements

6.1.6 *Combined Results*

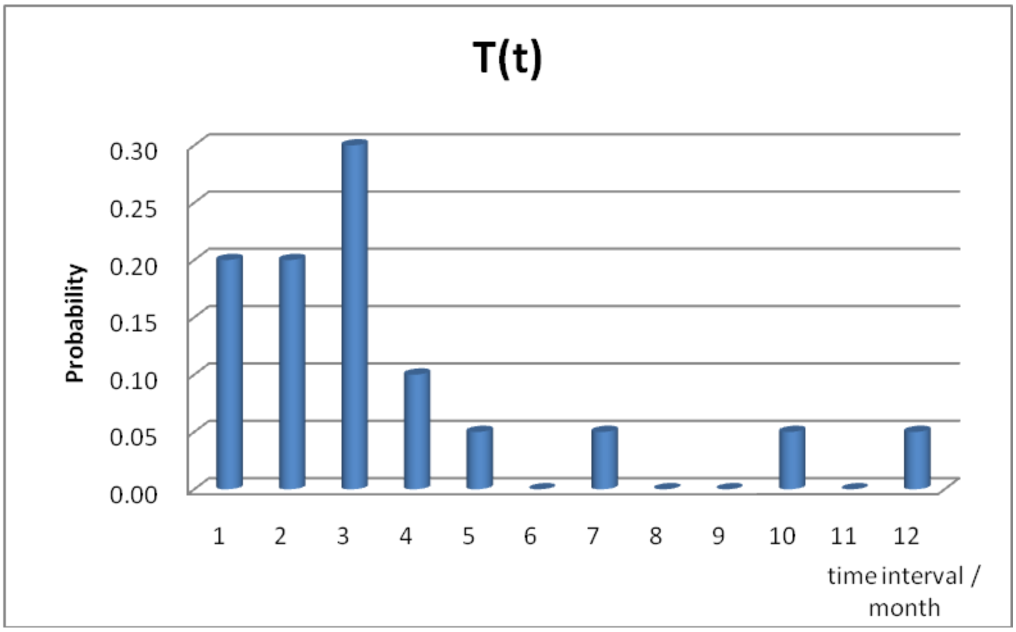
Having solved D(d(x,m)) and TP(x), Prediction Function P(x,m,t) can be calculated correspondingly. A combined result is shown below where the area with highest score indicates the most probable future crime locations. Given the locations and time of the first n-1 crime scenes in ‘The Yorkshire Ripper’ case, the probabilities of every point is plotted in the below graph. We can see that the actual nth crime location (Leeds) lies in the area where P(x,m,y) has the highest score. This verified that our prediction of location is correct and accurate.



6.2 Time Pattern

6.2.1 *Probability Analysis*

We categorize the time intervals between two crimes to find their probability distribution.



Time interval	1	2	3	4	5	6	7	8	9	10	11	12
Probability	0.2	0.2	0.3	0.1	0.05	0	0.05	0	0	0.05	0	0.05

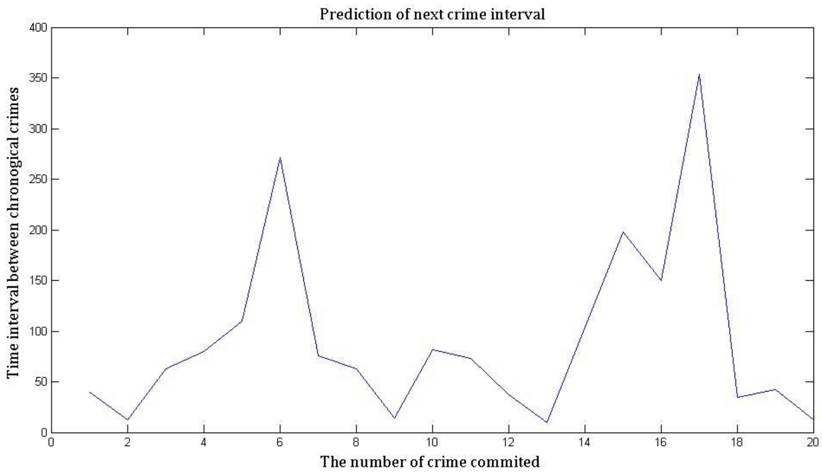
It can be re-expressed as in the below table so that a continuous time function can be derived.

Time interval	1	2	3	4	5-8	9-12
Probability	0.2	0.2	0.3	0.1	0.1	0.1

As time goes on, score function may vary as T(t) changes. For example, T(1)=0.2, T(2)=0.2, T(3)=0.3 etc.

6.2.2 *Period Analysis*

Case-specific periodic crime



The above graph illustrated how time interval of crimes is changing. Interpolation functions poorly fit the curves, and we are not able to use an existing function to describe its trend.

We can, however, tell from the patterns that the criminal is likely to commit 4-5 crimes in a short period of time, say every 2 months, and then 'take a rest' and ‘wait for the next opportunity’, which is reasonable as the police force is expected to increase after the happening of serial murders.

VI. Strength and Weakness

Strength:

1) Different models with distinctive strengths and weaknesses are adopted in analysis. The incorporation of different models eliminates the errors caused by one specific model. Various situations can be analyzed.
2) Location prediction allows for multiple anchor points, which increases the reliability and the stability of the model, and compensates for the errors in finding anchor points during geographical profiling.
3) A comprehensive prediction and analysis help researcher look deeper into the case. Even though only locations and time intervals are analyzed, our model analyzes the following variables and their correlations,
   The moving direction
   The distance from the anchor point
   The travel pattern between two crime locations
   The time intervals between crimes.
4) The prediction model is extendable. By evaluating T(t) and G(x), the prediction function is able to evaluate the influence of sophisticated demographic, geographic and time factors

.

Weakness:

As we have stated, this model is not perfect. That's just what we should do in the improved model.

1) The models are not verified by adequate statistics, due to the lack of data (especially the locations and time of murders) about serial murders.
2) The location prediction is only accurate to a relatively large piece of area, with a large deviation. The buffer zone width in decay function and the diameter of TP(x) circle will affect the precision. If data have large variance, the prediction will be less precise. Pinpoint prediction is not achieved.
3) Most models discussed in this article are sensitive to changes in input information. Error locations may result in large deviations in output geographical profile, and further bias the crime location prediction.
4) Some parts of the models are not generalized, making it hard to use the similar models to analyze other cases. Besides, the analysis of time patterns is more of a intuitive approach than a mathematical model.

VIII. Conclusions

8.1 Conclusions of the problem

- It is feasible to build up a model to predict the searching area based on the previous information on crime scenes.
- Various models are constructed for geographical profiling and sensitivity differs.

8.2 Methods used in our models

- Statistics methods are used for generating probability density function for some regular distribution and building up models.
- Geometric, physics methods are used for building up models.
- Interpolation is used for data regression.

8.3 Applications of our models

- Simplified prediction method can be applied to the marauder serial murder case with input of time and location of the previous scenes.
- Prediction method considers time, moving trend, geographical and demographical factors and is more adaptable to the real case, while requiring more information and empirical data given.

X. References

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