Supporting Online File for:

Simulation and Analysis of Animal Movement Paths using Numerus Model Builder

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1 MATHEMATICAL DESCRIPTION: MBCRW MODEL

We now introduce the mathematical description of the MBCRW model. This model describes a MBCRW with alternating centres of attraction O and P_i. Each daily movement will present a different P_i. The centre of attraction, indicated with P, switches as follows:

$$P = \begin{cases} O & \text{if } cos(\frac{2\pi t}{T}) > 0 \\ P_i & \text{otherwise} \end{cases}$$

where t indicates the elapsed time and T represents the length of the day. At time $t = 0$ P will be equal to O, switching after $\frac{T}{4}$ to P_i and to O again after $\frac{3}{4}T$.

Location data Given the initial position (x_0, y_0), the location coordinates are updated as follows:

$$\begin{aligned} x_{t+1} &= x_t + s_t \cos\theta_t \\ y_{t+1} &= y_t + s_t \sin\theta_t \end{aligned}$$

where s_t is the step length and θ_t is the absolute heading. Note that an equivalent description could define θ_{t+1} as function of the turning angle α_t, as follows:

$$\theta_{t+1} = \theta_t + \alpha_t$$

and apply the trigonometric functions to $(\theta_t + \alpha_t)$.

Step-length: s_t is uniformly distributed in $[s_{min}, s_{max}]$:

$$s_t \sim \text{UNIFORM}(s_{min}, s_{max})$$

Absolute heading: θ_t varies with time and location. We define θ_t as follows, where P represents the centre of attraction at time t:

$$\theta_{t+1} = \begin{cases} \theta^{c_P} & \text{if } z^u > f(d_t^P) \\ \theta_t + \theta^n & \text{otherwise} \end{cases}$$

θ^{c_P} is drawn from the distribution:

$$\theta^{c_P} \sim \text{UNIFORM}(\theta^P - (1 - corrP) \times \frac{\pi}{2}, \theta^P + (1 - corrP) \times \frac{\pi}{2})$$

where θ^P is the absolute heading towards the point P (function of the animal current position) and $corrP$ defines the heading correlation (0: no correlation, 1: maximum correlation).

z^u is drawn from the uniform distribution on $[0,1]$:

$$z^u \sim \text{UNIFORM}(0,1)$$

while the function f is defined as follows:

$$f(d_t^P) = \frac{1}{1+(d_t^P/d^{\text{crit}_P})^{\eta_P}}$$

It defines where the attraction is felt and therefore the range of movement. d_t^P is the distance from point P at time t, with $d^{\text{crit}_P} > 0$ and $\eta_P > 1$.

The random variable θ^n is drawn from the distribution:

$$\theta_n \sim \begin{cases} \text{UNIFORM}(-\pi,\pi) & \text{if } m=1 \\ \text{UNIFORM}(-(1-corrH)\times\pi,(1-corrH)\times\pi) & \text{if } m=2 \end{cases}$$

with heading correlation $corrH$. m describes 2 different modes: the first mode represents an uncorrelated random walk, within the critical distance, while the second one represents a walk with heading correlation greater than 0. The value of m can switch between the 2 values accordingly to the following transition matrix:

$$\begin{pmatrix} \theta_{11} & 1-\theta_{11} \\ 1-\theta_{22} & \theta_{22} \end{pmatrix}$$

with $\theta_{11}, \theta_{22} \in [0,1]$.

2 SIMULATION PARAMETERS

To define the parameters of our model, we established 5s as a time unit (17,280 in one day) and one space unit equal to 100m. In 5s, the travelled distance is around 7m (assuming straight walk and speed ≈ 5 km/h). We run the simulation for 172,800 time units (10 days); we set as initial location the origin O: (0,0), initial mode $m = 1$ and the centres of attraction as shown in Figure 1.

We use the following set of parameters:

Param name	Value	Param name	Value
s_{min}	0.05	η_P	3
s_{max}	0.09	corrH	0.8
T	17280	corrO	0.8
d^{crit_O}	50	corrP$_i$	0.8
$d^{crit_{P_i}}$	50	θ_{11}	0.995
η_O	3	θ_{22}	0.995

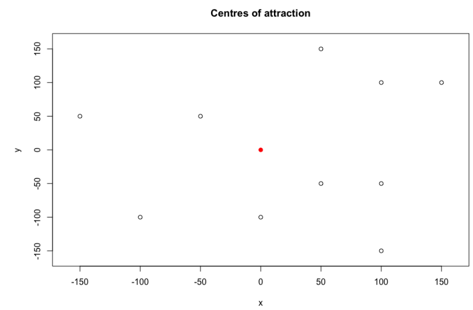

Figure 1: Centers of attraction O (in red) and the other 10 centers P_i. Note that the scale represents the spatial units in NMB.

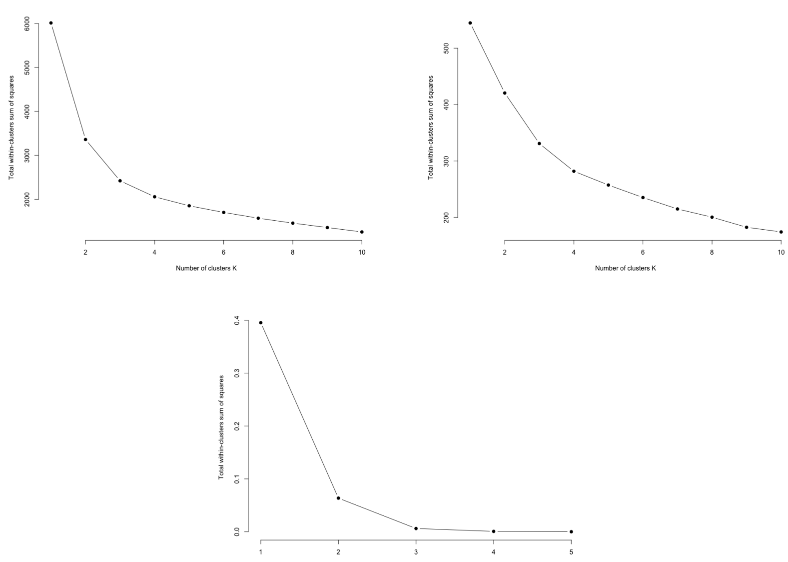

Figure 2: Elbow method - CAM and global

3 CLUSTERING ANALYSIS

The elbow method results are shown in Figure 2.

In this table we represent the number of metaFuMes in each CAM, from the analysis of the subsampled data of the MBCRW model.

CAM	metaFuME 1	metaFuME 2	metaFuME 3
1	6695	6314	0
2	4560	1093	5715
3	612	0	3205

4 M^3 PARAMETERS

$$M_C = \begin{bmatrix} 0.8040693 & 0.19593067 & 0.00000000 \\ 0.2217466 & 0.75000000 & 0.02825342 \\ 0.0000000 & 0.08571429 & 0.91428571 \end{bmatrix} \qquad M_1 = \begin{bmatrix} 0.5428309 & 0.4571691 & 0 \\ 0.4831565 & 0.5168435 & 0 \\ 0.5146437 & 0.4853563 & 0 \end{bmatrix}$$

$$M_2 = \begin{bmatrix} 0.4713947 & 0.27084843 & 0.2559668 \\ 0.3905443 & 0.23855440 & 0.3630815 \\ 0.3819397 & 0.04872121 & 0.5650052 \end{bmatrix} \qquad M_3 = \begin{bmatrix} 0.4257846 & 0 & 0.5742154 \\ 0.1603353 & 0 & 0.8396647 \\ 0.1291633 & 0 & 0.8708367 \end{bmatrix}$$

5 MODEL COMPARISON

Step length and turning angle distributions and time spent in each CAM for MBCRW model (Figures 3 and 4) and M^3 model (Figures 5 and 6)

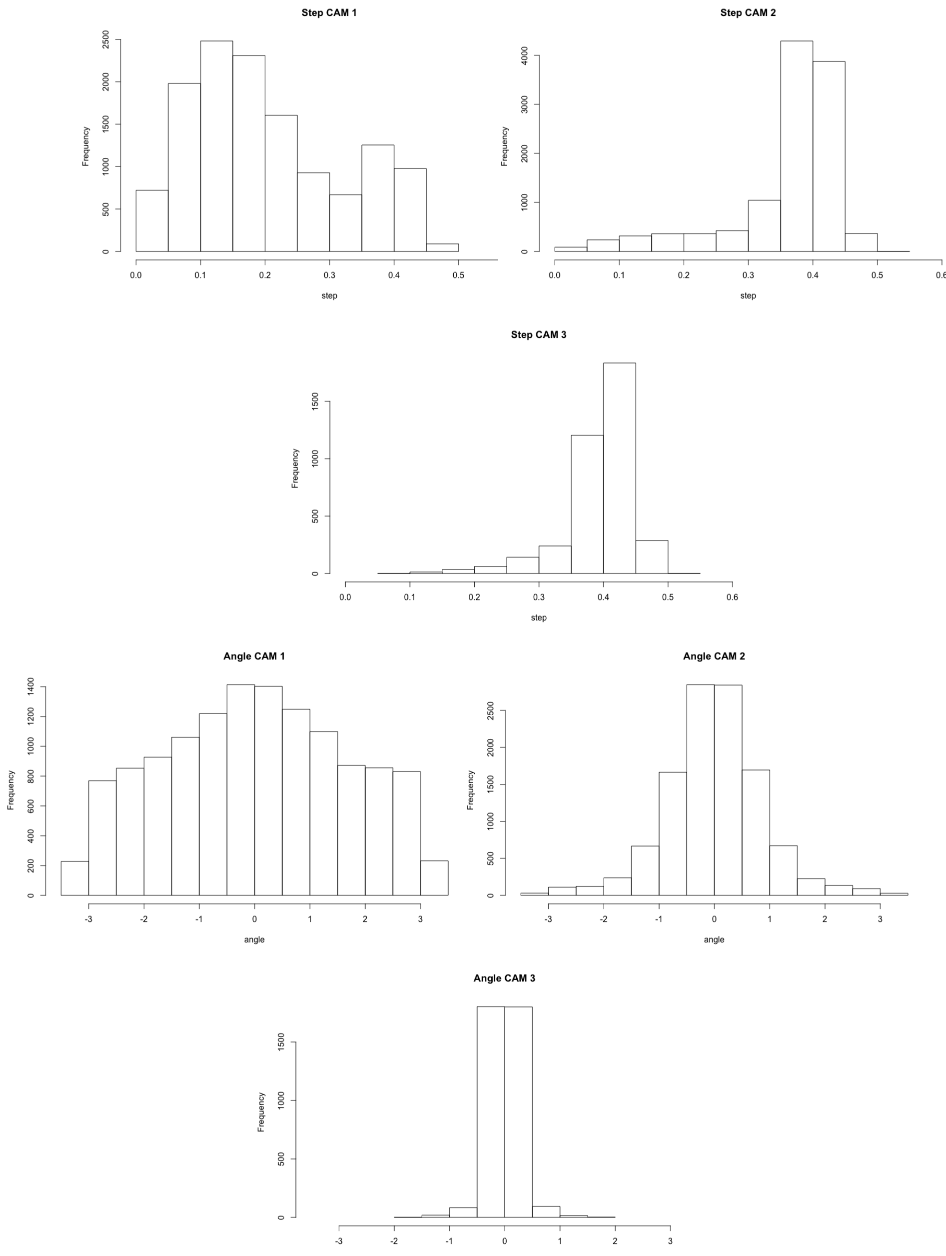

Figure 3: Step length and turning angle distribution for each CAM - MBCRW model

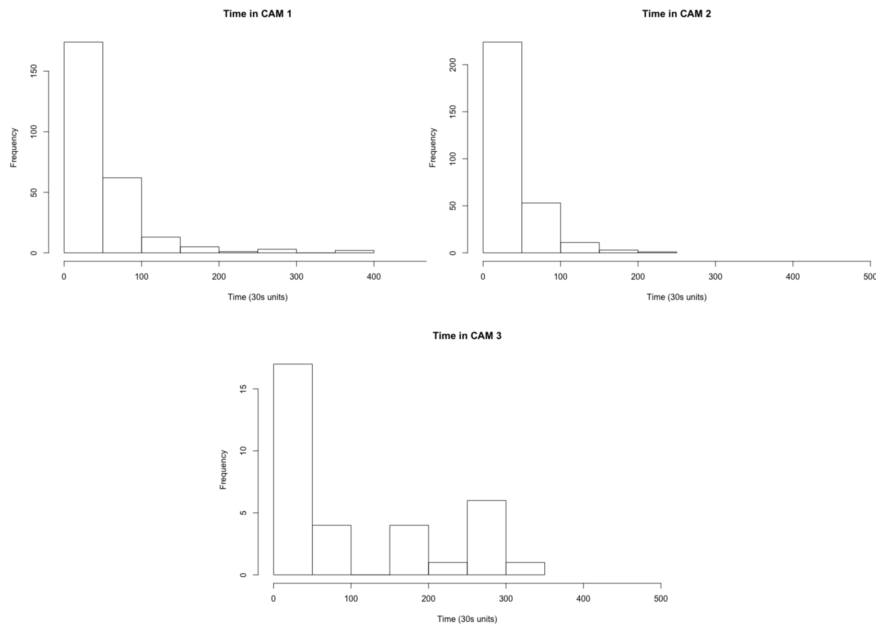

Figure 4: Distribution of time steps in each CAM, from MBCRW data

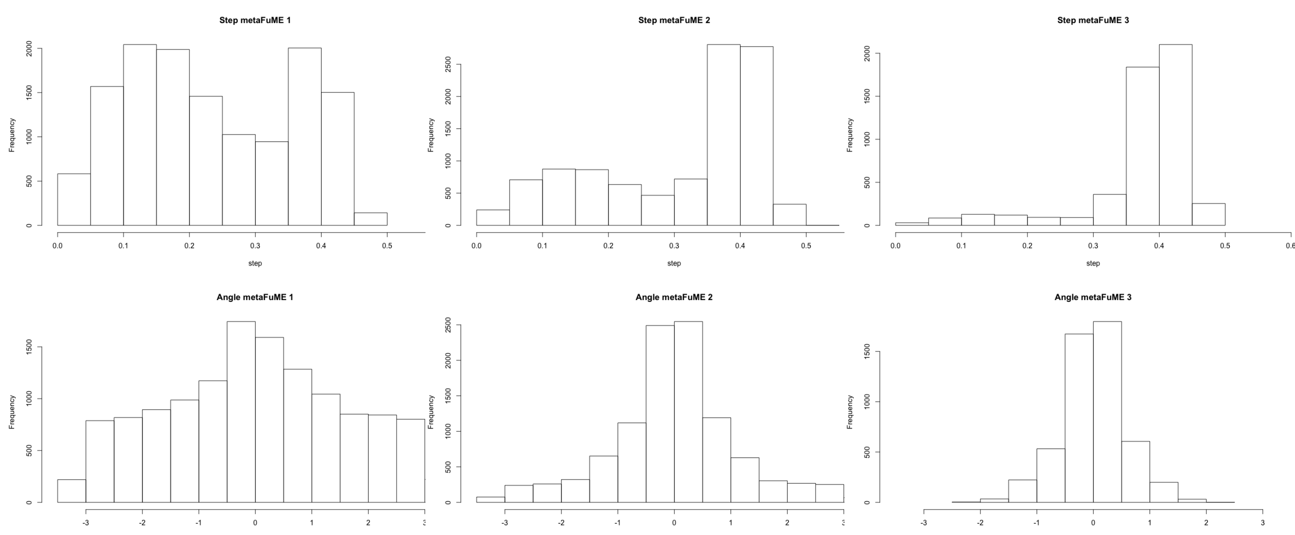

Figure 5: Step length and turning angle distribution for each CAM - M^3 model

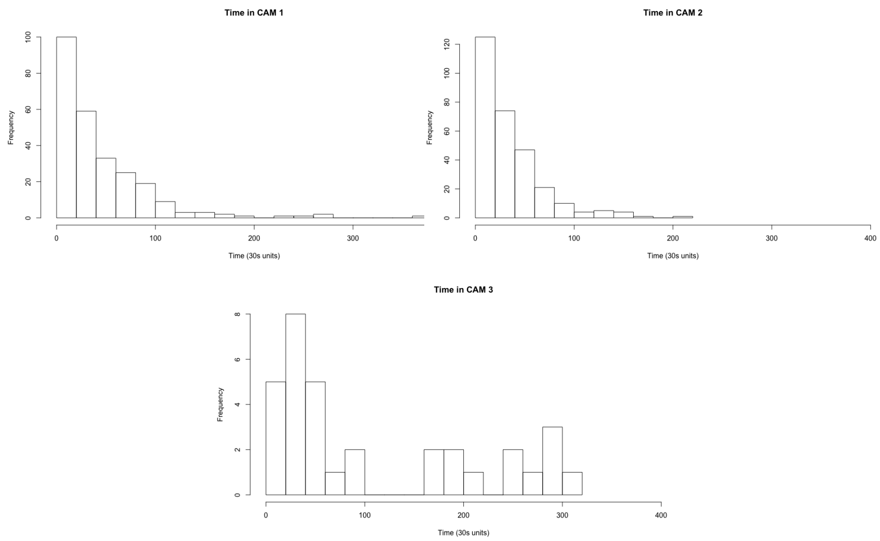

Figure 6: Distribution of time steps in each CAM, from M^3 data

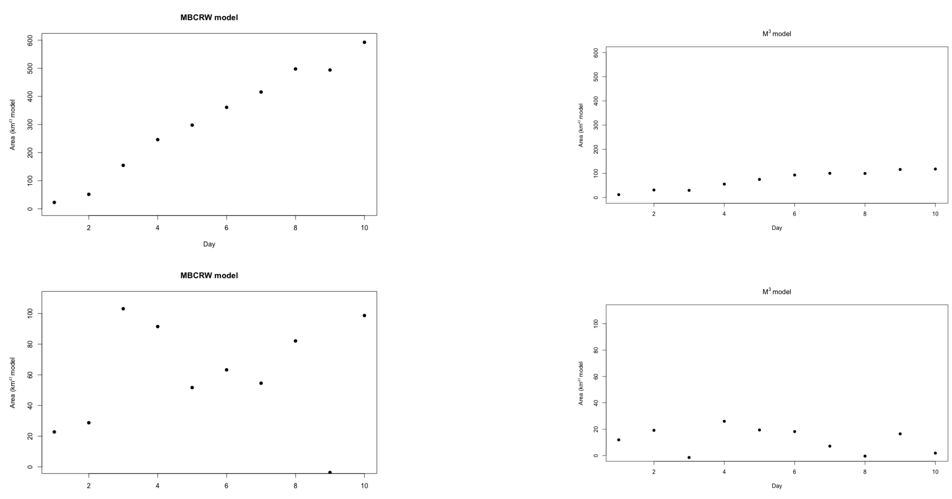

Figure 7: Area coverage over time, in total (first row) and each day (second row) for the 2 models

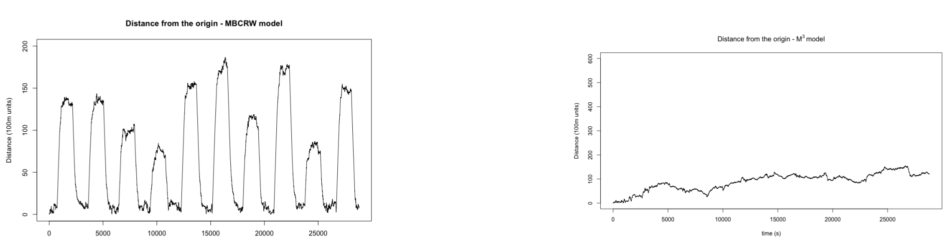

Figure 8: Distance from the origin over time for the 2 models