

## 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 MBCRW model. It describes a biased walk with alternating centres of attraction  $O$  and  $P_i$ . Each daily movement will present a different  $P_i$ . The movement will start from and around  $O$ , to move to and around  $P_i$  and back to  $O$ .

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

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  $\theta_t$  is the absolute heading. Note that an equivalent description could define  $\theta_{t+1}$  as function of the turning angle  $\alpha_t$ , 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:**  $\theta_t$  varies with time and location. We define  $\theta_t$  as follows, where  $P$  represents the centre of attraction at time  $t$ :

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

$\theta^{cp}$  is drawn from the distribution:

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

where  $\theta^P$  is the absolute heading towards the point  $P$  (function of the animal current position) and  $\text{corr}P$  defines the heading correlation (0: no correlation, 1: maximum correlation).

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

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

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  $\theta^n$  is drawn from the distribution:

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

with heading correlation  $\text{corrH}$ .  $m$  describes 2 different modes: the first mode represents a complete random movement, 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 (17280 in one day) and one space unit equal to 100m. In 5s, the distance is around 7m (assuming straight walk). We run the simulation for 172800 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	$\eta_P$	3
$s_{max}$	0.09	corrH	0.8
$T$	17280	corrO	0.8
$d^{\text{crit}_O}$	50	corrP <sub>i</sub>	0.8
$d^{\text{crit}_{P_i}}$	50	$\theta_{11}$	0.995
$\eta_O$	3	$\theta_{22}$	0.995

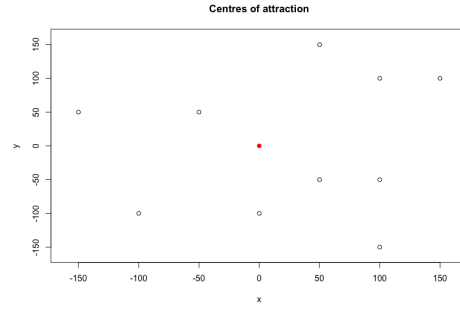


Figure 1: Centers of attraction  $O$  (in red) and  $P_i$ . Note that the scale represents the spatial units in NMB.

### 3 HMM ANALYSIS

The results of the HMM path segmentation are illustrated in Figure 2.

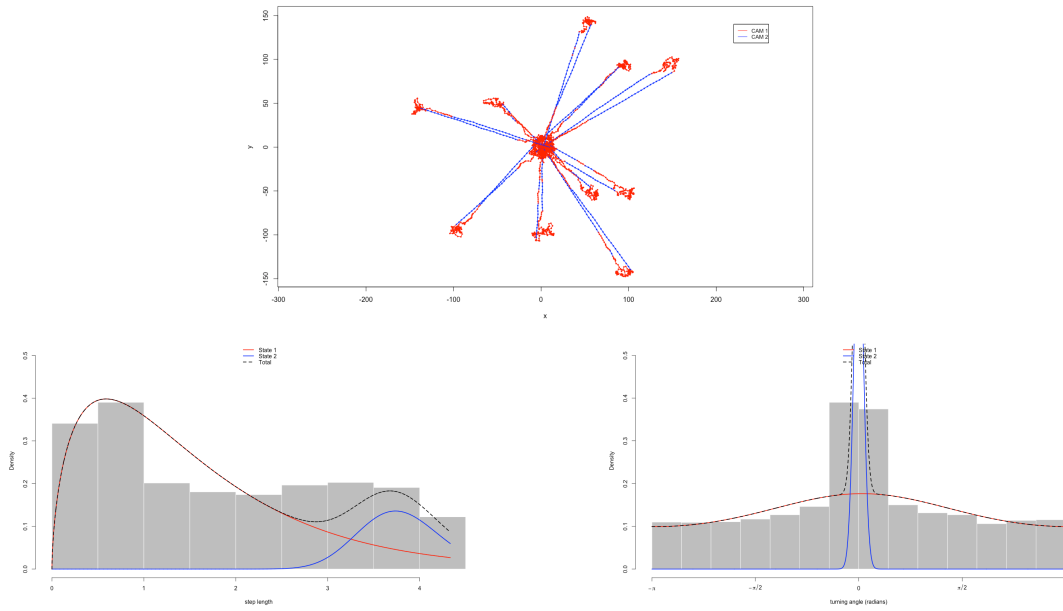


Figure 2: Results of the CAM extraction through HMM analysis

### 4 CLUSTERING ANALYSIS

The elbow method results are shown in Figure 3.

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	11541	12478	0
2	3425	0	895

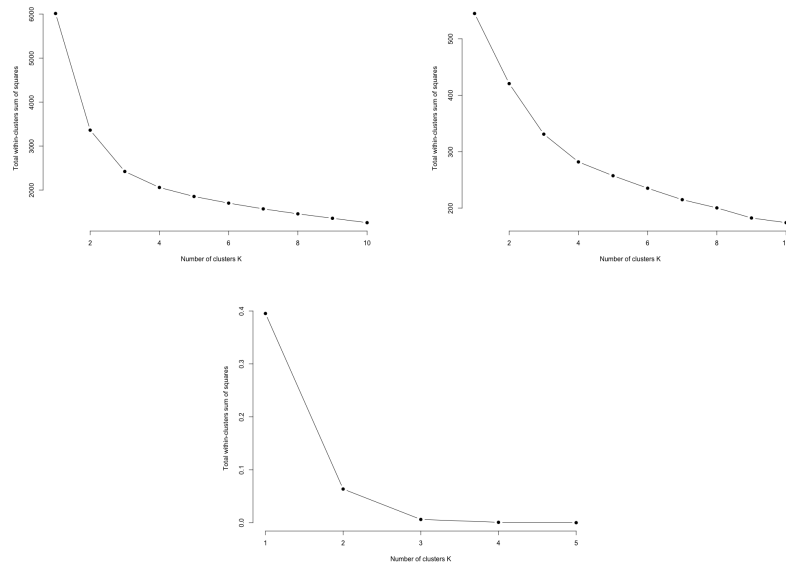


Figure 3: Elbow method - CAM and global

## 5 MODEL COMPARISON

Step length and turning angle distributions and time spent in each CAM for MBCRW model (Figures 4 and 5) and  $M^3$  model (Figures 6 and 7)

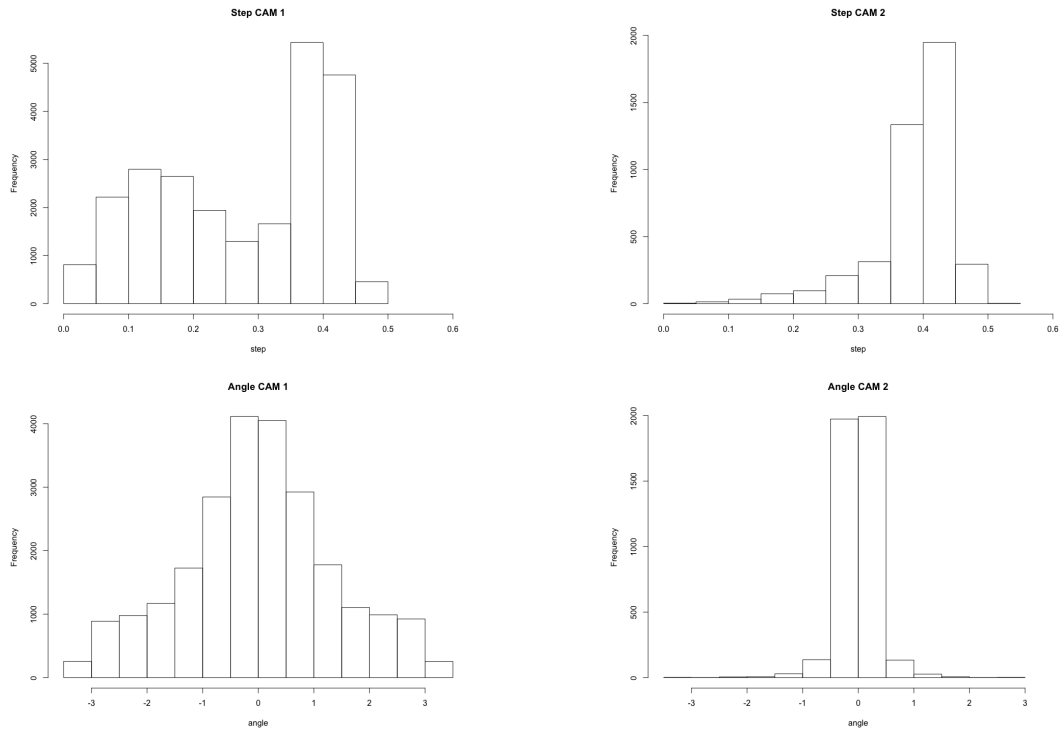


Figure 4: Step length and turning angle distribution for each CAM - MBCRW model

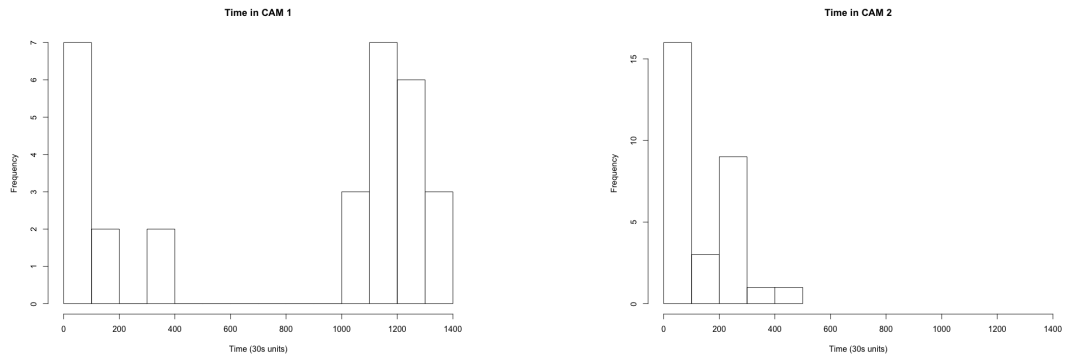


Figure 5: Distribution of time steps in each CAM, from MBCRW data

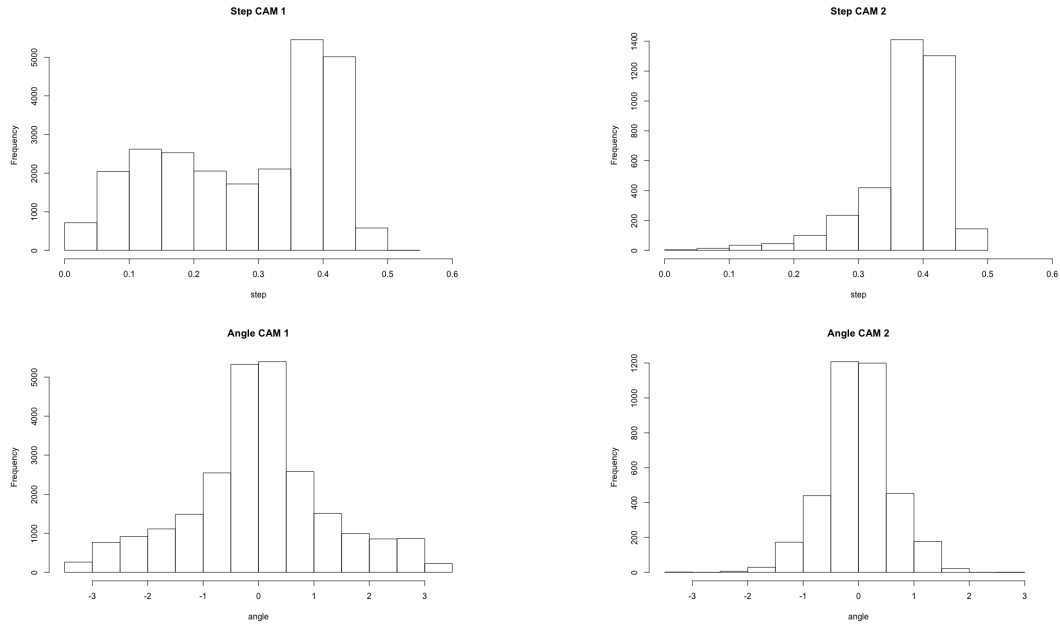


Figure 6: Step length and turning angle distribution for each CAM -  $M^3$  model

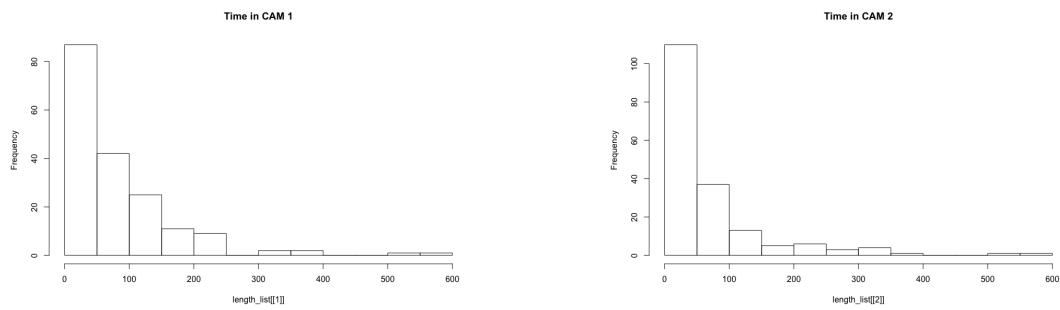


Figure 7: Distribution of time steps in each CAM, from  $M^3$  data