

$$\begin{aligned}
f_i &= f_{\min} + (f_{\max} - f_{\min}) \beta, \quad \beta \in [0, 1], \\
V_i^{t+1} &= V_i^t + (X_i^t + X^*) f_i, \\
X_i^{t+1} &= X_i^t + V_i^t,
\end{aligned}$$

Step 3. If the random number is greater than r_i , a new solution for the bat is generated by the following equation:

$$X_{\text{new}} = X_{\text{old}} + \epsilon A^t,$$

where ϵ is a random number, $\epsilon \in [-1, 1]$, and A^t represents the average loudness of all bats at time t .

$$\begin{aligned}
A_i^{t+1} &= \alpha A_i^t, \\
r_i^t &= r_i^0 [1 - e^{-\gamma t}],
\end{aligned}$$

where A_i^{t+1} and A_i^t denote the loudness at times t and $t + 1$, respectively; r_i^0 and r_i^t are the initial pulse rate and pulse rate at time t , respectively, α is a constant parameter in range $[0, 1]$, γ is a constant parameter, and $\gamma > 0$. As $t \rightarrow \infty$, $A_i^t \rightarrow 0$ and $r_i^t \rightarrow r_i^0$.

$$\text{fitness} = \alpha \cdot \text{intraCluster} + \beta \cdot SC + \zeta \cdot \left(\frac{1}{PC} + CE \right)$$

where:

- α , β , and ζ are weighting coefficients.
- intraCluster represents the intra-cluster distance.
- SC is the Silhouette Coefficient, which measures the separation between clusters.
- PC is the Partition Coefficient, used to evaluate clustering fuzziness.
- CE is the Cluster Entropy, which measures the uncertainty in cluster assignments.