List of Notations

$t_i$ \quad i$th task
$R_i$ \quad i$th Resource
$Fs(t_i)$ \quad Finishing time of task $t_i$
$Cost(R_i)$ \quad Cost of resource $R_i$ per time interval
$RU(R_i)$ \quad Time for which resource $R_i$ is utilized
$D(t_i)$ \quad Deadline of task $t_i$
$S(t_i)$ \quad Start time of task $t_i$
$B(t_i)$ \quad Submission time of task $t_i$
$W(t_i)$ \quad Waiting time of task $t_i$
$E(t_i)$ \quad Execution time of task $t_i$
Makespan \quad Makespan of a schedule
Flowtime \quad Flowtime of a schedule
TEC \quad Economic Cost of a schedule
Tard(t_i) \quad Tardiness of task $t_i$
Trnd(t_i) \quad Turnaround time for task $t_i$
Rel(R_i) \quad Reliability of a resource $R_i$
LT(R_i) \quad Time for which resource $R_i$ is leased
$\lambda(R_i)$ \quad Failure rate of a resource $R_i$
Reliability \quad Reliability of executing an application
$P$ \quad Power used by a server
$ut$ \quad CPU utilization of a server
$EC$ \quad Energy consumption of a server
$\tau_{ij}$ \quad Pheromone value related with task $t_i$ and resource $R_j$
$\eta_{ij}$ \quad Heuristic function of task $t_i$ and resource $R_j$
$\alpha$ \quad Impact of pheromone value
$\beta$ \quad Impact of heuristic function
$\omega$ \quad Inertia
$c1, c2$ \quad Acceleration coefficients
$rand1, rand2$ \quad Uniformly distributed random numbers between 0 and 1
$pbest$ \quad Best position of each particle
$gbest$ \quad Best position of entire particles in a population
\( X_i \) Position of a particle at iteration \( i \)

\( V_i \) Velocity of a particle at iteration \( i \)

\( L \) League Size

\( S_e \) Number of seasons

\( f \) Frequency of a bat

\( r \) Pulse rate of a bat

\( A \) Loudness of a bat

\( f_{\text{min}} \) Minimum value of frequency for a bat

\( f_{\text{max}} \) Maximum value of frequency for a bat

\( \beta \) Random vector drawn from a uniform distribution

\( \text{pos}_{\text{best}} \) Global best solution among all bats

\( \text{pos} \) Position of a bat

\( \text{vel} \) Velocity of a bat

\( \text{fitness}(x) \) Fitness value of a bat with position \( x \)

\( \text{av}, \text{bv}, \text{cv} \) Parameters for updating velocity

\( \text{as}, \text{bs}, \text{cs} \) Parameters for updating soil

\( e_{ij} \) Directed edge

\( \text{soil}(i,j) \) Soil of edge \( e_{ij} \)

\( \text{InitSoil} \) Initial soil on the edges of the graph

\( \text{InitVel} \) Initial velocity of Intelligent Water Drops

\( \text{LocalSoilUpdat} \) Local soil updating parameter

\( \text{GlblSoilUpdat} \) Global soil updating parameter

\( \text{Max}\_\text{iter} \) Maximum no. of iterations

\( N \) Number of Intelligent Water Drops

\( \text{soil}(IWD) \) Soil of \( IWD \)

\( \text{vel}(IWD) \) Velocity of \( IWD \)

\( \text{vc}(IWD) \) Visited node list of \( IWD \)

\( \Delta\text{soil}(i,j) \) Amount of soil removed from the edge \( e_{ij} \)

\( \text{iter}_{\text{best sol}} \) Iteration best solution

\( \text{best sol} \) Overall best solution

\( P(i,j) \) Probability of moving from node \( i \) to node \( j \)

\( \text{time}(i,j) \) Time required to travel edge \( e_{ij} \)

\( \text{HUD}(i,j) \) Heuristic undesirability of moving from node \( i \) to node \( j \)

\( q(IWD) \) Quality of \( IWD \)
$IWD_{itr, best}$  
$IWD$ with iteration best solution

$f(soil(i,j))$  
Inverse of $soil(i,j)$

$\varepsilon_s$  
Small positive constant

$g(soil(i,j))$  
Function to adjust the value of $soil(i,j) \geq 0$

$VM_j$  
$j$th virtual machine

$W$  
Workflow application

$T$  
Task Set

$E$  
Edge Set

$CP(VM_i)$  
Computing Capacity of $VM_i$

$ET(t_i,VM_j)$  
Execution time of a task $t_i$ on virtual machine $VM_j$

$Length(t_i)$  
Size of task $t_i$

$TT(t_i,t_k)$  
Data transfer time between task $t_i$ and $t_k$

$OutputFileSize(t_i)$  
Size of output file needs to be transferred from $t_i$

$BW$  
Average bandwidth between the VMs

$ST(t_i,VM_j)$  
Start time of a task $t_i$ on virtual machine $VM_j$

$Avail(VM_j)$  
Time at which virtual machine $VM_j$ is available

$ReadyTime(t_i,VM_j)$  
Time at which task $t_i$ is ready to execute on virtual machine $VM_j$

$FT(t_i,VM_j)$  
Finish time of task $t_i$ on virtual machine $VM_j$

$Makespan$  
Makespan of a workflow application

$soil(t_i,VM_j)$  
Soil between task $t_i$ and virtual machine $VM_j$

$\Delta soil(t_i,VM_j)$  
Amount of soil removed from the edge between $t_i$ and $VM_j$

$HUD(t_i,VM_j)$  
Heuristic undesirability of choosing $VM_j$ for $t_i$

$time(t_i,VM_j)$  
Time required to traverse the edge between $t_i$ and $VM_j$

$f(soil(t_i,VM_j))$  
Inverse of soil between task $t_i$ and virtual machine $VM_j$

$g(soil(t_i,VM_j))$  
Function to adjust the value of $soil(t_i,VM_j) \geq 0$

$P(t_i,VM_j)$  
Probability of selecting virtual machine $VM_j$ for task $t_i$

$rd$  
Random number between 0 and 1

$F(IWD)$  
Fitness of a solution found by a given IWD

$Nor\_FT(t_i,VM_j)$  
Normalized value of $FT(t_i,VM_j)$

$Nor\_RU(VM_j)$  
Normalized value of $RU(VM_j)$

$Initial\_Soil(t_i,VM_j)$  
Initial Soil between task $t_i$ and virtual machine $VM_j$
Random Number

Random Number between 0 and 1

exe_Time

Matrix containing execution time of each task on each VM

trans_Time

Matrix to store data transfer time between tasks in a workflow application

\( \bar{w}_i \)

Average execution time of \( t_i \) amongst all VMs

rank(\( t_i \))

Upward Rank or b-level of a task \( t_i \)

succ(\( t_i \))

Successor tasks of \( t_i \)

\( \Delta_{soil_{max}} \)

Maximum value of \( \Delta_{soil}( t_i, VM_j ) \)

\( \Delta_{soil_{min}} \)

Minimum value of \( \Delta_{soil}( t_i, VM_j ) \)

task_list

Tasks listed in increasing order

Perf_Deg(\( VM_j \))

Performance degradation percentage of virtual machine \( VM_j \)

LVM

Set of leased VMs in a schedule

Map

Task to VM mappings in a schedule

\( \sigma \)

Time-interval for billing

LST(\( VM_j \))

Time at which \( VM_j \) is acquired

LET(\( VM_j \))

Time at which \( VM_j \) is released

execost(\( VM_j \))

Execution Cost of \( VM_j \) before assigning \( t_{\text{rec}} \) to it

\( D \)

Deadline of the workflow application

SD(\( t_i \))

Sub-deadline of task \( t_i \)

\( ET_{PD_{max}}(t_i, VM_{fastest}) \)

Execution time of task \( t_i \) on the VM with maximum MIPS value considering its maximum limit of performance degradation

\( J \)

Highest number of tasks in a workflow which can execute in parallel

\( nt \)

Number of VM types

\( S \)

Workflow schedule

\( VM_{pool} \)

A pool of VMs

\( t_{\text{rec}} \)

next ready task

\( \text{temp}_TEC(VM_j) \)

Execution Cost of partial schedule when \( VM_j \) is selected for \( t_{\text{rec}} \)

\( \text{temp}_LST(VM_j) \)

Temporary leased start time of virtual machine \( VM_j \)

\( \text{temp}_LET(VM_j) \)

Temporary leased end time of virtual machine \( VM_j \)

\( \text{temp}_execost(VM_j) \)

Execution Cost of \( VM_j \) if it is selected for \( t_{\text{rec}} \)
Normalized value of temp_TEC(VM_j)

Normalized value of temp_TEC(VM_j)

Lower deadline

VM boot time

Reliability Index

Budget constraint of the workflow application

Number of Chromosomes

Diversity perimeter value of chromosome b

Crossover Probability

Mutation Probability

Number of switches per clock cycle

Total capacitance load

Frequency of the processor

Supply voltage

Capacitive power

Energy consumed when VMs are busy

Energy consumed when VMs are idle

Total energy consumption

Energy Consumption of partial schedule when VM_j is selected for t_rec

Normalized value of temp_Energy(VM_j)

Hypervolume of a non-dominated set

ith hypercube

C-metric for non-dominated sets X and Y

Maximum Deadline

Maximum budget

Minimum budget

ith objective function value of chromosome α

Deadline factor

Budget factor

Makespan of HEFT algorithm

Lowest supply voltage on VM_j

Set of idle slots on VM_j

kth idle slot on VM_j

Amount of idling time for d_{j,k}