

# Contents

<b>Certificate</b>	<b>ii</b>
<b>Copyright Transfer Certificate</b>	<b>iv</b>
<b>Preface</b>	<b>v</b>
<b>Acknowledgements</b>	<b>vii</b>
<b>Contents</b>	<b>ix</b>
<b>List of Figures</b>	<b>xiii</b>
<b>List of Tables</b>	<b>xv</b>
<b>Symbols</b>	<b>xvii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	2
1.1.1 Cloud computing . . . . .	3
1.1.2 Scientific workflows . . . . .	4
1.1.3 Virtual machine consolidation . . . . .	8
1.2 Motivation . . . . .	9
1.3 Thesis contributions . . . . .	10
1.4 Thesis organization . . . . .	11
<b>2 Review of Scheduling Approaches for Workflows in Clouds</b>	<b>15</b>
2.1 Introduction . . . . .	15
2.2 Overview of Workflow . . . . .	17
2.3 Workflow Scheduling in Clouds . . . . .	18
2.3.1 Cloud Workflow Architecture . . . . .	18

---

	User Interface . . . . .	18
	Workflow Engine . . . . .	19
	Administration and monitoring tools . . . . .	20
	Cloud Information Service (CIS) . . . . .	20
	Cloud Service Provisioning APIs . . . . .	20
2.4	Survey . . . . .	20
2.4.1	Workflows used and evaluation environment . . . . .	21
2.4.2	Application Model . . . . .	21
	Single workflow . . . . .	22
	Workflow ensembles . . . . .	22
	Multiple workflows . . . . .	22
2.4.3	Algorithm Scheduling Paradigm . . . . .	26
	Task-VM mapping . . . . .	26
	Resource provisioning . . . . .	26
	Scheduling objectives . . . . .	26
	Optimization Strategy . . . . .	32
2.4.4	Resource model . . . . .	34
	VM Leasing model . . . . .	34
	VM Type equality . . . . .	34
	VM Pricing model . . . . .	34
	VM Delays . . . . .	34
	VM Core-count . . . . .	36
2.4.5	Energy optimization techniques . . . . .	36
2.4.5.1	Sequences tasks merging . . . . .	36
2.4.5.2	Parallel tasks merging . . . . .	37
2.4.5.3	VM Reuse . . . . .	38
2.4.5.4	Task slacking . . . . .	38
2.4.5.5	DVFS . . . . .	38
2.4.5.6	Per-core DVFS . . . . .	39
2.4.5.7	Task Migration . . . . .	39
2.4.5.8	Clustering of Tasks/ Workloads . . . . .	39
2.4.5.9	VM Power utility . . . . .	40
2.4.5.10	VM Placement . . . . .	40
2.4.5.11	Limiting CPU utilization . . . . .	40
2.4.5.12	PM mode switch . . . . .	41
2.4.5.13	Pareto optimality . . . . .	41
2.4.6	Summary of surveyed algorithms and future directions . . . . .	43
2.5	Conclusion . . . . .	57
3	<b>A heuristic-based energy-efficient and cost-aware scheduling algorithm with deadline constraints</b>	59
3.1	Introduction . . . . .	60

---

3.2	Related work . . . . .	61
3.3	Problem Modeling . . . . .	63
3.3.1	Datacenter Model . . . . .	63
3.3.2	Application Model . . . . .	63
3.3.3	Cost Model . . . . .	64
3.3.4	Energy Model . . . . .	65
3.3.5	Scheduling Model . . . . .	66
3.4	Proposed Methodology . . . . .	66
3.4.1	Task Scheduling with HEFT algorithm . . . . .	67
3.4.2	Calculate Ratio of Effectiveness (RE) Values . . . . .	67
3.4.3	Selecting RE Threshold . . . . .	69
3.4.4	Slack reclaiming . . . . .	72
3.4.5	ECWS Algorithm . . . . .	73
3.5	Performance Evaluation . . . . .	75
3.5.1	Self-comparison . . . . .	77
3.5.2	Results comparison with others . . . . .	78
3.6	Conclusion . . . . .	82
<b>4</b>	<b>A heuristic-based scheduling algorithm for energy and reliability optimization</b> . . . . .	<b>83</b>
4.1	Introduction . . . . .	83
4.2	Related work . . . . .	84
4.3	System models . . . . .	86
4.3.1	Datacenter Model . . . . .	86
4.3.2	Application Model . . . . .	87
4.3.3	Power Model . . . . .	88
4.3.4	System Reliability . . . . .	88
4.3.5	Problem Specification . . . . .	90
4.4	Algorithm implementation . . . . .	90
4.4.1	Task rank calculation algorithm . . . . .	90
4.4.2	Task clustering algorithm . . . . .	91
4.4.3	Sub-Target Time Distribution algorithm . . . . .	92
4.4.4	Cluster-VM mapping algorithm . . . . .	93
4.4.5	Slack algorithm . . . . .	93
4.4.6	EERS Algorithm . . . . .	94
4.5	Performance evaluation . . . . .	96
4.5.1	Performance Evaluation with different workloads . . . . .	98
4.5.2	Performance Evaluation with different number of VMs . . . . .	98
4.6	Conclusion . . . . .	99
<b>5</b>	<b>A meta-heuristic-based virtual machine consolidation algorithm</b> . . . . .	<b>101</b>
5.1	Introduction . . . . .	101
5.2	Related work . . . . .	103

---

5.3	System Model . . . . .	104
5.4	Theory of Water Wave . . . . .	105
5.5	Energy Efficient VM Consolidation with WWO . . . . .	106
5.5.1	Propagation for Energy Efficient VMC . . . . .	107
5.5.2	Refraction for Energy Efficient VMC . . . . .	107
5.5.3	Breaking for Energy Efficient VMC . . . . .	108
5.5.4	Algorithm framework . . . . .	108
5.6	Experimental setup and results . . . . .	110
5.6.1	Simulation Results . . . . .	111
5.7	Conclusion . . . . .	114
<b>6</b>	<b>A hybrid scheduling algorithm with virtual machine consolidation</b>	<b>117</b>
6.1	Introduction . . . . .	118
6.2	Related Work . . . . .	119
6.3	System Models . . . . .	121
6.3.1	Data center Model . . . . .	121
6.3.2	Application Model . . . . .	122
6.3.3	Energy Model . . . . .	123
6.3.4	Problem Specification . . . . .	124
6.4	Proposed Algorithm . . . . .	124
6.4.1	Task Scheduling . . . . .	125
6.4.2	VM Consolidation . . . . .	125
6.4.3	Water Wave based VM Consolidation . . . . .	128
<b>Propagation:</b>		129
<b>Refraction:</b>		129
<b>Breaking:</b>		130
6.5	Performance Evaluation . . . . .	132
6.5.1	Experimental Settings . . . . .	132
6.5.2	Self-Comparison Experiments . . . . .	133
6.5.3	Comparison Experiments with Others . . . . .	134
6.6	Conclusion . . . . .	142
<b>7</b>	<b>Conclusions and Future research directions</b>	<b>145</b>
7.1	Conclusions . . . . .	145
7.2	Future Research Directions . . . . .	147
<b>Bibliography</b>		<b>149</b>
<b>List of Publications</b>		<b>166</b>

# List of Figures

1.1	A sample workflow . . . . .	2
1.2	Classical cloud service offerings . . . . .	3
1.3	Montage . . . . .	5
1.4	CyberShake . . . . .	6
1.5	Epigenomics . . . . .	7
1.6	SIPHT . . . . .	7
1.7	LIGO . . . . .	8
1.8	Global data center IP traffic from 2013 to 2021 . . . . .	10
1.9	Thesis organization . . . . .	11
2.1	Workflow management architecture . . . . .	19
2.2	The process of sequence task merging . . . . .	37
2.3	The process of parallel task merging . . . . .	37
3.1	Mutual time between two VMs. . . . .	68
3.2	Self-comparison in cost. . . . .	77
3.3	Self-comparison in energy. . . . .	78
3.4	Comparison with others in cost. . . . .	79
3.5	Comparison with others in energy consumption. . . . .	79
3.6	Comparison experiments in resource utilization. . . . .	81
3.7	Average resource utilization. . . . .	82
4.1	Clustering of Tasks . . . . .	91
4.2	The pseudo-code of the EERS algorithm . . . . .	95
4.3	<b>a)</b> Energy consumption and <b>b)</b> Reliability for various workloads on CyberShake Workflow . . . . .	97
4.4	<b>a)</b> Energy consumption and <b>b)</b> Reliability for diffrent number of VMs on CyberShake Workflow . . . . .	97
4.5	<b>a)</b> Energy consumption and <b>b)</b> Reliability for various workloads on Montage Workflow . . . . .	98
4.6	<b>a)</b> Energy consumption and <b>b)</b> Reliability for diffrent number of VMs on Montage Workflow . . . . .	99
5.1	Shallow and deep water wave models . . . . .	105

5.2	15 Cloudlets . . . . .	112
5.3	20 Cloudlets . . . . .	112
5.4	30 Cloudlets . . . . .	113
5.5	60 Cloudlets . . . . .	113
5.6	90 Cloudlets . . . . .	114
5.7	120 Cloudlets . . . . .	114
6.1	Self-comparison experiments in energy consumption and resources utilization. . . . .	136
6.2	Comparison experiments of VM consolidation algorithm in energy consumption. . . . .	137
6.3	Energy consumption and Resources utilization on Montage Workflow. . . . .	137
6.4	Energy consumption and Resources utilization on CyberShake Workflow. . . . .	137
6.5	Energy consumption and Resources utilization on LIGO Workflow. . . . .	138
6.6	Energy consumption and Resources utilization on Sipt Workflow. . . . .	138
6.7	Energy consumption and Resources utilization on Epigenomics Workflow. . . . .	138
6.8	Average resource utilization on different Workflows. . . . .	142

# List of Tables

2.1	Workflow(s) used and evaluation environment . . . . .	23
2.2	Algorithm classification for the application model . . . . .	27
2.3	Scheduling model . . . . .	28
2.4	Techniques classification based on resource model . . . . .	35
2.5	Techniques used to optimize energy . . . . .	42
2.6	Comparison of Energy-Aware Techniques . . . . .	44
3.1	The ECWS algorithm summary . . . . .	75
3.2	VM parameters . . . . .	76
3.3	Cost-efficiency of ECWS over other algorithms . . . . .	80
3.4	Energy-efficiency of ECWS over other algorithms . . . . .	81
4.1	Simulation Environment Parameters . . . . .	96
5.1	Parameters in the WWO-VMC approach. . . . .	111
5.2	Amount of energy consumption of HP G3 server at different load levels. .	111
6.1	The EASVMC algorithm summary . . . . .	131
6.2	Workflow benchmark setup . . . . .	132
6.3	VM Instance Specifications . . . . .	132
6.4	WWO Parameters. . . . .	133
6.5	Number of VM migrations and Switched off hosts . . . . .	139
6.6	The EASVMC performance for large workloads . . . . .	141
6.7	Energy-savibg of the EASVMC algorithm . . . . .	142