MULTI-OBJECTIVE SCIENTIFIC WORKFLOW SCHEDULING ALGORITHM IN MULTI-CLOUD ENVIRONMENT FOR SATISFYING QoS REQUIREMENTS

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To my late father

“Farid Ebrahim Ramadhan”

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Associate Professor Rohaya Latip, PhD
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Cloud computing is a high-performance distributed computing platform that integrates large-scale services. It facilitates many scientific and engineering, as well as business workflow applications. However, current workflow applications come with various Quality of Service (QoS) objectives and constraints, such as makespan, cost, reliability, resource utilization and security, which pose serious QoS management challenges with respect to satisfying the objectives under specific constraints. In addition, the cloud environment is complex, highly uncertain with chances of failures at all levels (human, software, hardware, security). Therefore, one of the major concerns of users is getting assurance of the needed QoS for their applications, especially in tight cases.

These have also led another issue in scheduling workflow for cloud computing which are minimizing workflow makespan and cost simultaneously while satisfying the reliability constraint, improving overall QoS satisfaction, as well as increasing the reliability and minimizing completion time of the scheduled process with fault-intrusion tolerance.

There are three (3) main objectives laid out in this thesis, to tackle these issues. First, to propose a multi-objective and reliability constraint handling algorithm (FR-MOS) that controls the reliability constraint by determining the reliability constraint coefficient according to the value of the resource utilization. Second, to propose a minimum-weight-based multi-objective algorithm (MOS-MWO), which is based on Particle Swarm Optimization (PSO) technique and a novel minimum weight optimization approach, that improves user's QoS satisfaction. Third, to propose a fault-intrusion-tolerant algorithm (FITSW), which is based on both fault and intrusion-tolerant techniques, to decrease the adverse impact caused by different faults (accidental and malicious) in cloud computing

systems. All the proposed algorithms are simulated using the popular cloud simulator, Workflowsim 1.0.

Results of the experiments prove that the multi-objective and reliability constraint handling (FR-MOS) algorithm significantly minimizes the makespan by 9% and cost by 10% compared to the benchmark algorithm under the reliability constraint. This was accomplished by determining the value of the reliability constraint coefficient based on the resource utilization of each alternative and selecting the best results from various alternatives with several reliability constraints. Moreover, the improvements of different QoS metrics values achieved by using a minimum-weight-based multi-objective algorithm (MOS-MWO) for scheduling scientific workflows are better than those of the previous work which used the Pareto optimization method. MOS-MWO can thus be applied in cloud-based applications to effectively schedule workflow while achieving significant improvement in the QoS satisfaction rate (QSR) to 4.8% compared with the multi-objective scheduling algorithm (MOS). The average of different workflows objectives shows that MOS-MWO algorithm yields better makespan compared with the MOS algorithm. With the MOS-MWO algorithm, makespan is reduced by 40%, cost also reduced by 3 % and risk probability reduced by 86%. MOS-MWO increases the resource utilization by 15% than MOS, and the reliability increase by 2%. Finally, the workflow completion time of the fault-intrusion-tolerant and deadline-aware algorithm (FITSW) decreased by 15% for all datasets when compared with the previous work, and the intrusion tolerance increased due to the high success rate of workflow execution.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ALGORITMA PENJADUALAN ALIRAN KERJA SAINTIFIK PELBAGAI OBJEKTIF DALAM PERSEKITARAN BERBILANG AWAN UNTUK MEMUASKAN KEPERLUAN QoS

Oleh

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Pengkomputeran awan ialah platform pengkomputeran teragih berprestasi tinggi yang menyepadukan perkhidmatan-perkhidmatan berskala besar. Ia memudahkan pelbagai aplikasi saintifik, kejuruteraan, serta aliran kerja perniagaan. Walau bagaimanapun, aplikasi aliran kerja semasa datang dengan pelbagai objektif dan kekangan Kualiti Perkhidmatan (QoS), seperti *makespan*, kos, kebolehpercayaan, penggunaan sumber dan keselamatan, yang menimbulkan cabaran pengurusan kualiti perkhidmatan (QoS) yang serius untuk memenuhi objektif di bawah kekangan tertentu. Di samping itu, persekitaran awan adalah kompleks dan tidak stabil, dengan kemungkinan kegagalan di semua peringkat (manusia, perisian, perkakasan, dan keselamatan). Oleh itu, salah satu kebimbangan utama pengguna ialah mendapatkan jaminan kualiti perkhidmatan (QoS) yang diperlukan untuk aplikasi mereka, terutamanya dalam kes yang kompleks.

Ini juga telah membawa kepada isu-isu lain dalam menjadualkan aliran kerja untuk pengkomputeran awan, iaitu meminimumkan penetapan aliran kerja dan kos secara serentak sambil memenuhi kekangan kebolehpercayaan, meningkatkan kepuasan kualiti perkhidmatan QoS secara menyeluruh, serta meningkatkan kebolehpercayaan dan meminimumkan masa penyiapan proses yang dijadualkan dengan toleran kesalahan-pencerobohan.

Bagi menangani isu-isu tersebut, terdapat tiga (3) objektif utama yang digariskan dalam tesis ini. Pertama, untuk mencadangkan algoritma pengendalian kekangan berbilang objektif dan kebolehpercayaan (FR-MOS) yang mengawal kekangan kebolehpercayaan dengan menentukan pekali kekangan kebolehpercayaan mengikut nilai penggunaan sumber. Kedua, untuk mencadangkan algoritma multi-objektif berasaskan berat minimum (MOS-MWO), yang berdasarkan teknik Pengoptimuman Kerumunan Zarah (PSO) dan pendekatan pengoptimuman berat minimum baharu, yang meningkatkan

kepuasan kualiti perkhidmatan QoS pengguna. Ketiga, untuk mencadangkan algoritma toleran kesalahan-pencerobohan (FITSW), yang berdasarkan kedua-dua kesalahan dan teknik toleran-pencerobohan, untuk mengurangkan kesan buruk yang disebabkan oleh kesalahan yang berbeza (tidak sengaja dan berniat jahat) dalam sistem pengkomputeran awan. Semua algoritma yang dicadangkan disimulasikan menggunakan simulator awan yang popular, Workflowsim 1.0.

Keputusan eksperimen membuktikan bahawa algoritma pengendalian kekangan berbilang objektif dan kebolehpercayaan (FR-MOS) meminimumkan makespan sebanyak 9% dan kos sebanyak 10% dengan ketara berbanding algoritma penanda aras di bawah kekangan kebolehpercayaan. Keputusan ini dicapai dengan menentukan nilai pekali kekangan kebolehpercayaan berdasarkan penggunaan sumber setiap alternatif dan memilih keputusan terbaik daripada pelbagai alternatif dengan beberapa kekangan kebolehpercayaan. Selain itu, peningkatan nilai metrik QoS berbeza yang dicapai dengan menggunakan algoritma berbilang objektif berasaskan berat minimum (MOS-MWO) untuk menjadualkan aliran kerja saintifik adalah lebih baik daripada kajian terdahulu yang menggunakan kaedah pengoptimuman Pareto. Oleh itu, MOS-MWO boleh digunakan dalam aplikasi berasaskan awan untuk menjadualkan aliran kerja dengan berkesan sambil mencapai peningkatan ketara dalam kadar kepuasan QoS (QSR) kepada 4.8% berbanding dengan algoritma penjadualan berbilang objektif (MOS). Purata objektif aliran kerja yang berbeza menunjukkan bahawa algoritma MOS-MWO menghasilkan makespan yang lebih baik berbanding dengan algoritma MOS. Dengan algoritma MOS-MWO, makespan dikurangkan sebanyak 40%, kos juga dikurangkan sebanyak 3% dan kebarangkalian risiko dikurangkan sebanyak 86%. MOS-MWO meningkatkan penggunaan sumber sebanyak 15% daripada MOS, dan kebolehpercayaan meningkat sebanyak 2%. Akhir sekali, masa penyiapan aliran kerja algoritma toleran kesalahan-pencerobohan dan sedar-tarikh akhir (FITSW) menurun sebanyak 15% untuk semua set data jika dibandingkan dengan kajian terdahulu, dan toleransi pencerobohan meningkat disebabkan oleh kadar kejayaan pelaksanaan aliran kerja yang tinggi.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
ACC	Average Computation Cost
ACO	Ant Colony Optimization
ADAS	Adaptive Data-aware Scheduling
ALO	Ant Lion Optimization
ANFIS	Adaptive Network-based Fuzzy Inference System
APMWSA	An Adaptive Privileged Multi-objective Workflow Scheduling Algorithm
APSO	Alternative PSO
BDHEFT	Budget and Deadline Constrained Heterogeneous Earliest Finish Time Algorithm
BDLS	Bi-objective Dynamic Level Scheduling
BOGA	Bi-objective Genetic Algorithm
BoT	Bag of Tasks
BPSO	Binary PSO
CCSH	Cost-conscious Scheduling
CD	Crowding Distance
CMOHEFT	Constraint-MOHEFT
C-PSO	Catfish PSO
CPU	Central Processing Unit
CSP	Cloud Service Provider
CU	Compute Unit
DAG	Directed Acyclic Graphs
DC	Data Center

DFTWS	Dynamic Fault-Tolerant Workflow Scheduling
DLS	Dynamic Level Scheduling
DNA	Deoxyribonucleic Acid
DNCPSO	Directional and Non-local-convergent Particle Swarm Optimization
DPSO	Discrete Particle Swarm Optimization
DSH	Replication Scheduling Heuristic
DVFS	Dynamic Voltage and Frequency Scaling
EC2	Elastic Compute Cloud
EDF	Earliest-Deadline-First
EFT	Earliest Finish Time
EMS-C	Evolutionary Multi-objective Scheduling for Cloud
EU	End User
FCFS	First Come First Serve
FCWS	Fault-tolerant Cost-efficient Workflow Scheduling Algorithm
FDHEFT	Fuzzy Dominance sort-based HEFT
FITS	Flexible Image Transport
FITSW	Fault-Intrusion Tolerant Scientific Workflow
FR	Fuzzy Resource Utilization
FR-MOS	Fuzzy Resource Utilization Multi-objective scheduling Algorithm
FTS	Fault-Tolerant Scheduling
GA	Genetic Algorithm
GAPSO	Genetic Algorithm and Particle Swarm Optimization
GB	Giga Byte
GRASP	Greedy's Randomized Adaptive Search Process

GWO	Grey Wolf Optimizer
H/W	Hardware
HEA-TaSDAP	Hybrid Evolutionary Algorithm for Solving the Task Scheduling and Data Assignment Problem
HEFT	Heterogeneous Earliest Finish Time
HPSO	Hybrid Particle Swarm Optimization
HR	Horizontal Reduction
HSA	Harmony Search Algorithm
IaaS	Infrastructure as a Service
IDEA	Improved Differential Evolution Algorithm
IGD	Inverted Generational Distance
INHIBITOR	Intrusion Tolerant Scheduling Algorithm in cloud- based Scientific Workflow System
IPIREM	Intrinsic-plasticity-inspired Rescheduling Execution Model
IPSO	Improved PSO
ITSW	Intrusion Tolerant Scientific Workflow
ITSW-RV	Intrusion Tolerant Scientific Workflow with Random Number of VMs
IWD-GA	Intelligent Water Drop and Genetic Algorithm
LAPSO	Look-ahead PSO
LIGO	Laser Interferometer Gravitational Wave Observatory
LJFN	Longest Job on Fastest Node
MAPSO	Multi-objective Workflow Scheduling Strategy based on PSO
MCPCP	Multi Cloud Partial Critical Path
MI	Million Instructions
MLE	Maximum Likelihood Estimates

MODPSO	Multi-objective Discrete Particle Swarm Optimization
MOEA	Multi-objective Evolutionary Algorithm
MOHEFT	Multi-Objective Heterogeneous Earliest Finish Time
MOP	Multi-objective Optimization
MOPSO	Multi-objective Particle Swarm Optimization
MOS-MWO	Multi-objective scheduling Algorithm with Minimum Weight Optimization Method
MPSO	Modified PSO
MSMO	Multi-Swarm Multi-Objective Optimization
MSMOOA	Multi-swarm Multi-objective Advanced Operation Algorithm
MWO	Minimum Weight Optimization Method
NP	Non-deterministic Polynomial
NPSO	New Novel PSO
NSGA	Non-dominated Sorting Genetic Algorithm
NSPSO	Non-Dominated Sort Particle Swarm Optimization
OWS-A2C	Online Workflow Scheduling algorithm based on Adaptive resource Allocation and Consolidation
PaaS	Platform as a Service
PAES	Pareto-Archived Evaluative Strategy
PAES	Pareto-Archived Evaluative Strategy
PBM	Population-based Metaheuristic
PCP	Partial Critical Paths
PCPA	Partial Critical Paths Algorithm
PCPA	Partial Critical Paths Algorithm
PMLSH	Pareto Multi-objective List Scheduling Heuristic

PSHA	Probabilistic Seismic Hazard Analysis
PSO	Particle Swarm Optimization
PSO-DS	PSO Discrete Adaptation Algorithm
PSOi	PSO-based algorithm
PSO-SC	Service Cost
PTE	Parallel Task Execution
QoS	Quality of Service
QSR	Quality of Service Satisfaction Rate
RA	Resource Adjustment
RAM	Random Access Memory
RDLS	Reliable Dynamic Level Scheduling
RDPSO	Revised Discrete Particle Swarm Optimization
RHDPSO	Rotary Hybrid Discrete PSO
RI	Resubmission Impact
S/W	Software
SA	Simulated Annealing
SaaS	Software as a Service
SABA	Safety Plan and Budget Scheduling Algorithm
SCAS	Security and Cost Aware Scheduling
S-CLPSO	Set-based Comprehensive Learning PSO
SGT	Strain Green Tensors
SJFN	Shortest Job on Fastest Node
SKOPE	Skeleton Framework for Performance Exploration
SLA	Service Level Agreement

SLPSO	Self adaptive Learning PSO
SM	Server Manager
SOP	Single-objective Optimization
SPEA	Strength Pareto Evolutionary Algorithm
SPSO	PSO with Adaptive Inertia Weight
S-PSO	Set-based PSO
SW	Scientific Workflow
SWF	Scientific Workflow
TryXy	Trusted Virtual Private Storage Cloud for Cloud based Scientific workflows
TS	Tabu Search
UML	Unified Modeling Language
VM	Virtual Machine
VNS	Variable Neighborhood Search
WMS	Workflow Management System
XML	Extensive Markup Language

CHAPTER 1

INTRODUCTION

This chapter presents the research background, problem statements and motivations of the current work. It also discusses the research objectives, the scope of the research and research significance. In addition, it highlights the research contributions which justify the benefits and clarify the implications of this research. Finally, this chapter summarizes the organization of this thesis.

1.1 Background

In the last two decades, there has been a revolution in science and the way technology is used. Scientific and technological advances have solved several multidisciplinary and complex issues. However, they are also associated with multiple challenges. Workflows were previously used to describe business processes only. The scientific community accepted the concept and began to model complex experiments and applications as workflows. The term "scientific workflow" describes the process of determining the sequence of tasks that is necessary to handle any computational process. The primary distinction between business and scientific workflows is that business workflows are typically task-oriented and control-driven while scientific workflows can be both data-driven and control-driven (Deelman et al., 2009). In modern science, large-scale experimentation and extensive simulations generate enormous amounts of data on a regular basis. The science of workflow design, management, and execution is made up of sequences of steps that make up certain complex processes. Workflows help in the management of such time-consuming and data-intensive procedures by laying out the steps in the correct order. Tasks take data from previous tasks or data sources and perform predefined calculations. The output is then passed on to the tasks that follow.

Workflow Management System (WMS) is used to manage workflows. At first, an abstraction of a high-level workflow (abstract workflow) is designed. Abstract workflow refers to the logical order in which the workflow steps will be carried out. At this time, the resources are not linked to the tasks. The WMS locates and maps appropriate resources to complete workflow task execution; the resulting workflow is referred to as concrete workflow. Later stages provide a provenance mechanism that saves the history of workflow data that is useful in determining the optimization approaches and parameters during the resource mapping process. For future relevant experimentation and study, the provenance data is important (Liew, 2012). DISPEL (Bonanza, 2013), BPEL (Slominski, 2007) and YAWL (Ter Hofstede & van der Aalst, 2005) are some of the languages that can be used to express workflows. Taverna1 is one of the WMSs that has its own workbench for writing and developing workflows.

A variety of issues must be addressed in order to enable efficient workflow management. Workflow scheduling, workflow application modelling, information service, resource discovery, data management, and fault management are all topics to consider. From the user-centric point of view, scheduling workflow application in a multi-cloud environment to meet the QoS demands of users is the most challenging. The scheduling problem, on the other hand, falls into the category of non-deterministic polynomial complete (NP-complete) problems since it involves composing a collection of distributed services for workflow tasks. For such problems, no known algorithm is able to generate the optimal solution within polynomial time. Also, users now have multiple objectives and constraints for executing their applications. Another challenging aspect of the service composition problem is how to ensure the selected services can guarantee the expected QoS delivery such as deadline constraints. This is because many of these services exhibit dynamic QoS behavior at runtime. Moreover, a service-oriented multi-cloud environment is complicated and complex with numerous uncertainties and chances of failure at various levels. These and many other scheduling challenges are demonstrated in Figure 1.1 (Chandrashekar, 2015).

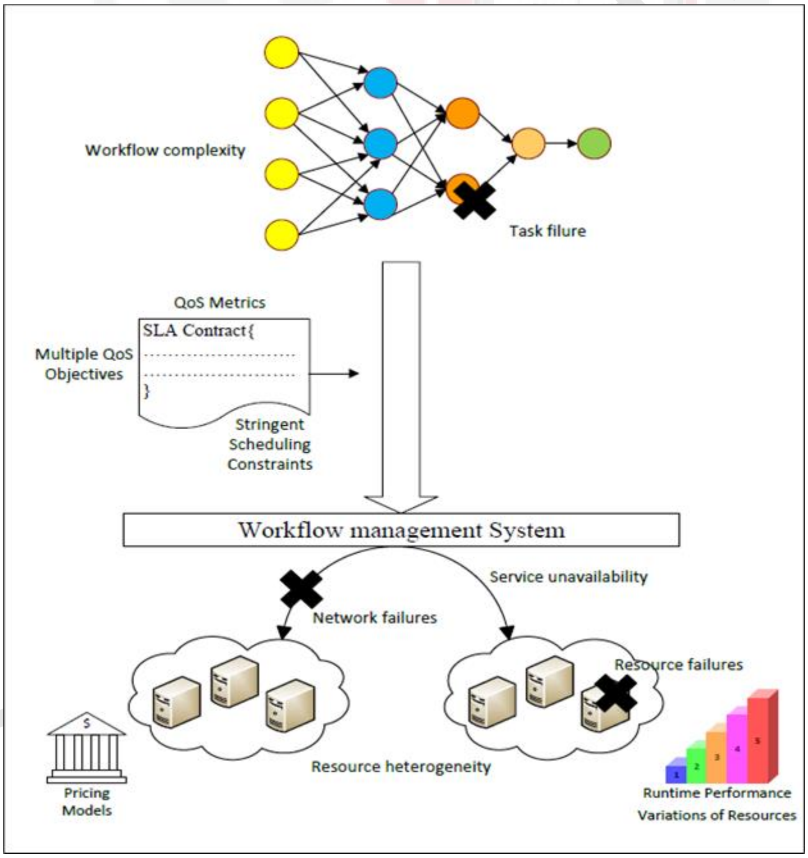

Figure 1.1 : Challenges in Scheduling Workflow Applications on Cloud Computing Environment (Chandrashekar, 2015)

Consequently, the QoS-aware service composition problem is a complex optimization and trade-off problem. Despite the fact that the problem can be solved by performing an exhaustive search, the time taken to produce a solution is enormous. In a service-oriented environment, scheduling decisions must be made in the shortest time possible, dependable and efficient because competition for services is very high among users as well as service providers.

1.2 Problem Statement

Cloud workflow scheduling is well-recognized to be an NP-complete problem (Madni et al., 2016), and workflow scheduling in a multi-cloud environment is even more difficult (I. Gupta et al., 2016; B. Lin et al., 2015). Particularly, in a multi-cloud environment, services are provided by multiple individual cloud IaaS platforms and computing resources are pooled into one or more composite services. Then, to meet the QoS requirements, choosing an appropriate combination of services from multiple IaaS platforms is quite challenging (Cui et al., 2017; Rodriguez & Buyya, 2014; Z. Zhu et al., 2016). Some of the recent works in this area have been able to achieve workflow scheduling in multi cloud environment with focusing on either single or two objectives, however, the deployed approaches do not considered multi-objective scheduling problem, especially with respect to maintaining user satisfaction and service provider requirements, for all five QoS metrics including, makespan, cost, reliability, resource utilization and risk probability.

Although, many studies have been conducted to address the scientific workflow scheduling problems in cloud environment with significant contributions, several issues have been left unaddressed. Three of such problems are described in what follows:

1. Scientific workflow scheduling algorithms are mostly based on stochastic auxiliary methods which iteratively search and produce trade-off solutions. For the design of large-scale workflow systems with tight reliability constraints, these algorithms cannot search effectively due to the stochastic feature and therefore most of them cannot produce satisfactory makespan-cost trade-offs (P. Han et al., 2021). Most of the existing studies used deep learning equations to determine the scheduling constraints by using a fixed learning rate which allow them to compare the different alternatives with tight constraints (Y. Li et al., 2021). This limits its feasible solutions due to that learning rate. Comparing different alternatives with some adaptive methods can produce better makespan-cost trade-offs than those using fix learning rate, as a result of comparing disparate alternatives with different learning rate (Kayacan & Khanesar, 2016), however this method has not been considered in this context to achieve a better performance.
2. Another concern is that previous studies on cloud workflow scheduling concentrate fewer (not more than three) objectives and thus, there is a lack of effective studies and approaches for problems with over three objectives (Saeedi et al., 2020). In this respect, from the extensive review of literature done in this research work, it became evident that most of the QoS scheduling models

use the Pareto optimizing method to solve such problems multi-objective problems. A pareto optimizing method produces a solution with conflicted objectives, so to optimize one objective of that solution means make the other worse. However, this method also has it's particular drawbacks that degrades the efficiency of multi-objective evolutionary algorithms (MOEAs) dramatically in multi-objective optimization problems, where the number of objectives exceeds three according to (Cappelletti et al., 2016; Gómez-Skarmeta et al., 1999). For instance, Pareto optimization method does not give an optimum solution but proffers an equally effective set of configurations, also it requires a higher number of iterations thus taking a long time to make a better final decision with high QoS satisfaction rate.

3. Resource sharing for cloud-based scientific workflows is vulnerable and as such adversaries can destroy them directly or indirectly by side channels, virtual machine (VM) escape and other means leading to disruption or incorrect outputs. To protect the scheduling system from these types of attacks the intrusion tolerance is required. Only a few works separately study intrusion tolerance in workflow scheduling in the cloud, and all of them ignored the delay due to intruder access and monitoring of the intermediate data without altering or modifying them thereby negatively affecting the scheduling reliability and execution time (Bhattarai et al., 2015; W. Yu et al., 2017). This is a significant issue because, cloud-based scientific workflows are commonly used in important scientific research fields and their failure would lead to huge losses (Yawen Wang et al., 2021).

1.3 Motivation

The problem of scheduling workflow in a multi-cloud computing environment is quite complicated (I. Gupta et al., 2016; B. Lin et al., 2015) and it is regarded as NP-complete (Madni et al., 2016). This is because independent cloud IaaS offers this service by putting their computing resources together. Particularly, meeting the QoS requirements is a daunting challenge since selecting the optimal combination of services from these independent IaaS platforms is somewhat difficult (Z. Li et al., 2015; Rodriguez & Buyya, 2014; Z. Zhu et al., 2016). Like other distributed systems, cloud computing is vulnerable to software faults, hardware failures and power malfunction (Jeannot et al., 2012). These unavoidable issues lead to task and workflow failures during the course of executing sophisticated workflow applications (Hwang & Kesselman, 2003; D. Poola et al., 2016). Hence, it is important to ensure reliability while scheduling workflow in clouds (A. Singh & Chatterjee, 2017). Although cloud providers consider different reliability parameters, it is important that users pay attention to the workflow's reliability constraints.

Most of the previous studies on scheduling scientific workflow incorporated different constraints by using deep learning equations with fixed user-defined learning rates as a constraint coefficient (Hu et al., 2018; Z. Li et al., 2016, 2021; P. Wang et al., 2020). A comparison between alternatives is done according to that tight constraint with fixed learning rate. The initial user defined learning rate degrade the efficiency of multi-objective scheduling algorithm, because it is not related to the actual performance of the scheduling algorithm. To improve makespan-cost tradeoffs, there is a need for a better mechanism to capture and control the reliability constraint effectively. These motivate this research to aim at improving successful scheduling of scientific workflow in cloud computing as the subjects of focus.

Fuzzy logic is integrated with a multi-objective algorithm to generate the reliability constraint coefficient depending on the value of the resource utilization. This compares different alternatives with different reliability constraints to improve the performance of MOS in terms of makespan-cost trade-off.

Scheduling scientific workflow with more than three objectives is another challenge in cloud computing. Hence, an efficient workflow scheduling algorithm must strike a balance between several QoS objectives. One way of striking such a balance is adopting Pareto optimal method that allows users to select the best result within an acceptable set of solutions. With the aforementioned in mind, the mean drawbacks of Pareto optimization method is that not giving an optimum solution but proffers an equally effective set of configurations, also it requires a higher number of iterations thus taking a long time to make a better final decision (Cappelletti et al., 2016).

Hence, taking advantage of aggregation and normalization methods is a good option. The minimum weight optimization method (MWO) in this case used to get the optimum solution among all alternatives. Using (MWO) provides a better quality of service satisfaction rate (QSR).

There are many threats in clouds due to multi-tenant coexistence, co-residential attacks (Atya et al., 2017), side-channel attacks (Z. Wang et al., 2016; Yinqian Zhang et al., 2014), and VM escape attacks (J. Wu et al., 2017). A large number of tasks and intermediate data contained in scientific workflows can easily be targeted by attackers. Monitoring data by attacker without altering or modifying that data delays the finish time of executing tasks, this type of intrusion is ignored by the most intrusion tolerance techniques which affected the reliability and finish time of the workflow execution.

To address these issues, new models are required to improve the reliability of the workflow's output. These induce this research to aim at improving the reliability of the workflow's output by using virtual clusters comprised of many VMs. They are used to execute workflow tasks which check the correctness of intermediate data of each sub-task, with sub-deadline constraint. These form the motivation behind this research.

1.4 Research Objectives

The main objective of this thesis is to propose an efficient workflow scheduling algorithm for satisfying multiple QoS requirements and improving the reliability of workflow execution. The sub-objectives are discussed in detail as follows:

1. To propose an enhanced reliability constraint handling algorithm for scheduling scientific workflow based on particle swarm optimization (PSO) method. The algorithm produces satisfactory makespan-cost trade-offs while considering reliability constraints with adaptive fuzzy resource utilization method, which determine the constraint coefficient.
2. To propose a multi-objective scheduling algorithm with a novel decision-making approach named the minimum weight optimization (MWO), that concentrate on five QoS objectives (Makespan, cost, reliability, resource utilization and risk probability) to provides an appropriate alternative for all optimal solutions with better QoS satisfaction.
3. To propose a fault-intrusion-tolerant and deadline-aware algorithm for scheduling scientific workflow based on heterogeneous earliest finish time (HEFT) method. With considering the delay that caused by intruder access and monitoring data without modify them, the suggested algorithm minimizes the makespan while enhancing the security and improving the reliability of workflow execution.

1.5 Research scope

This research focuses on developing reliable scheduling algorithms for scientific workflows in the multi-cloud environment for satisfying QoS requirements. Firstly, the research aims to provide reliable solutions to users, therefore, it concentrates on reliability constraints based on Fuzzy resource utilization. The primary focus is on handling the reliability constraint to minimize the violation of the constraint. Since the scheduling optimization problem involves a trade-off of multiple objectives, the researcher also focuses on applying efficient metaheuristic and auxiliary scheduling techniques to develop an optimization strategy for better QoS satisfaction. Finally, it studies how to ensure reliable execution using an error detecting mechanism. Specifically, the focus will be to develop fault-intrusion tolerant algorithm to enhance scheduling reliability.

1.6 Research Significance

The outcomes of this research will be beneficial to academic researchers and practitioners working in scientific workflow scheduling in cloud computing environments. The research's main aim is, as noted earlier:

“Multi objective based scientific workflow scheduling algorithms in multi cloud environment for satisfying QoS requirements “

The following are the main outcomes of this research that are expected based on this aim:

- Scheduling scientific workflow with Fuzzy resource utilization for reducing the cost and the makespan of the of scheduling process in multi-cloud environment. The proposed approach helps to get better makespan-cost trade-offs for considered scenario. At the same time, these lower makespan-cost trade-offs will increase service providers' profitability, using all computing resources to gain a competitive advantage over other cloud providers.
- The proposed multi-objective scheduling algorithm with a novel decision-making approach (MWO), has a direct impact on satisfying the QoS requirements by reducing makespan and cost for service consumers. Furthermore, it is expected that the proposed approach helps in reduce risk probability and increase reliability for service providers, by wisely utilization the resources (VMs).
- The proposed fault-intrusion tolerance approach provides an efficient platform to optimally schedule scientific workflow by considering accidental and malicious attacks. This can improve the reliability and enhance the security, with reducing the finish time of workflow execution.
- Several benefits can be achieved from conducting the extensive literature review.

The outcome of this research would be helpful for the academic researchers in providing clearer and complete understanding of satisfying QoS requirements of scheduling scientific workflow in cloud environment, by providing the following expected outcomes:

- A variety of taxonomies of QoS constraints for scientific workflow scheduling challenges, objectives, tools, and many other algorithms.
- Correlation between different QoS constraints and their profitability to service consumer and service providers.
- Future opportunities in this field of research. This would offer up new avenues for high impact research that encourages innovative values with cloud computing and scientific workflow scheduling.

1.7 Research Contributions

This thesis studies the QoS-aware scheduling of workflow applications in a multi-cloud environment. The main contribution of this thesis is the enhancement of the existing scheduling strategies for satisfying users' QoS requirements. The contribution is achieved in three parts and summarized as follows:

1. A proposed multi-objective and reliability constraint handling algorithm (FR-MOS) that minimizes cost and makespan. The PSO-based algorithm applies Fuzzy resource utilization to determine the value of the reliability constraint coefficient. Providing different reliability coefficients to each alternative according to the capacity of the resource utilization makes the algorithm to produce better makespan-cost trade-offs, which can be shown clearly using the Pareto-front set.
2. A proposed minimum-weight-based multi-objective scheduling algorithm (MOS-MWO) that improves the QoS satisfaction for users and service providers and minimizes the optimization time. The algorithm optimizes scheduling solutions by iteratively searching for and producing good solutions based on PSO as the baseline algorithm. MOS-MWO evaluates and selects the best solutions according to the weights of the specified alternatives. Such weights are also used to establish the inertia weight by using an adaptive strategy that enhances the efficiency and performance of PSO. Applying the minimum weight optimization (MWO) approach helps to provide an appropriate alternative for all feasible solutions.
3. A proposed fault-intrusion-tolerant and deadline-aware algorithm for scheduling scientific workflow (FITSW) that improves the reliability and enhances the security of workflow execution using a new decision mechanism that tracks and evaluates the confidence of the intermediate data between tasks during execution. FITSW considers the effects of accidental and malicious faults on cloud-based scientific workflows. The sub-deadline method applied checks that each task can be performed without any VM's failure. During the scheduling process, each task is replicated and executed by the task-executer containing heterogeneous VMs. A task scheduling approach based on recycling resources is introduced to guarantee that the task executors remain in a clean state.

1.8 Thesis Organization

This thesis is organized as follows:

Chapter 1 presents the research background, problem statements and motivations of this work. It discusses the research objectives, scope and research significance. It also highlights the research contributions that justify the benefits of this research.

Chapter 2 presents the previous workflow scheduling and other research that addressed issues relating to workflow QoS and fault tolerance techniques in cloud computing.

Chapter 3 explores the research framework and explains the research stages. The experiment setup and multi-cloud architecture, as well as the performance metrics and validation of the model, are also presented in this chapter.

Chapter 4 presents the proposed scientific workflow scheduling algorithm with Fuzzy resource utilization. It describes the algorithm and shows the enhancement in the results obtained with respect to makespan-cost trade-offs. Moreover, it presents the performance evaluation in terms of convergence, diversity and uniformity.

Chapter 5 demonstrates the proposed multi-objective algorithm with MWO decision-making approach for scheduling scientific workflow. It explains the operations of the algorithm and provides the performance evaluation in terms of QoS satisfaction rate, convergence, diversity and uniformity.

Chapter 6 presents the proposed fault-intrusion-tolerant and deadline-aware algorithm for scheduling scientific workflow. The chapter also highlights the performance evaluation of the algorithm and compares it with other previous works.

Chapter 7 concludes this thesis and recommends promising directions for further research.

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