Universitat de Lleida

Virtual Machine Scheduling for Energy and SLA Optimisation based in Metaheuristics and Forecasting Techniques in Cloud Computing

Sergi Vila Almenara

http://hdl.handle.net/10803/687570

Universitat de Lleida

Ph.D. THESIS

Virtual Machine Scheduling for Energy and SLA Optimisation based in Metaheuristics and Forecasting Techniques in Cloud Computing

Doctoral Programme in Engineering and Information Technology

by

Sergi Vila Almenara

Thesis Supervisors

Fernando Guirado Fernández

Josep L. Lérida Monsó

University of Lleida

July, 2022

Virtual Machine Scheduling for Energy and SLA Optimisation based on Metaheuristics and Forecasting Techniques in Cloud Computing

by

Sergi Vila Almenara

Submitted to the University of Lleida on July, 2022

Abstract

Ever since computing and the Internet became part of our society, large datacenters have been necessary to serve customers, businesses, governments and the scientific community. Machine virtualisation has made it possible to encapsulate multiple instances of operating systems on a single physical device, allowing for lower power consumption in resource sharing. Because these resource requirements vary over time, corrections in the allocation of virtual machines to other physical machines must be applied to guarantee Service Level Objectives (SLOs).

The main purpose of this thesis is to contribute to Cloud environments by improving energy consumption and Quality of Service (QoS), by means of the Service Level Agreement (SLA), through techniques that allow the correct decisions to be executed at the correct moment. Resource planning allows the needs and demands of each physical and virtual machine to be adapted to improve the overall system performance. By performing optimal task assignations and Virtual Machine migrations, datacenters become more stable and efficient, requiring less supervision and corrections, guaranteeing the indispensable number of active physical machines running properly and avoiding the performing of redundant actions.

Two types of environments were dealt with during this thesis. Firstly, static environments were the focus, where the Bin Packing Problem was solved to optimise the energy and makespan proposing a multi-objective genetic algorithm (BLEMO). The next focus was on dynamic environments, in which different proposals were developed. Initially, a virtual machine selection algorithm (WPSP) was proposed to reduce the number of migrations and SLA violations. The proposal included a VM to host allocation algorithm (MDG) in order to reduce the total inter-host communications, and so optimising the network bandwidth. Next, the use of Bollinger Bands (BB) was combined with the NeuralProphet framework (BB+NeoPro) to generate long-term predictions. These enable consolidation of the VM to host allocations, reducing the number of migrations, energy consumption and SLA Violations. Furthermore, an improved version of BB+NeoPro was proposed by combining WPSP, BB and Facebook Prophet (WBF). This proposal was tested with different Cloud workloads from several providers in order to validate its robustness.

The analysis of the results showed how all the evaluated metrics obtained substantial benefits thanks to the multi-purpose exploration of the search space in the case of static environments, and the careful and adapted observation of the available data in dynamic environments that allowed better decisions to be taken.

Thesis Supervisors
Fernando Guirado Fernández
Josep L. Lérida Monsó

Resumen

Desde que la informática e Internet se integraron en nuestra sociedad, se ha requerido el uso de grandes centros de datos para dar servicio a clientes, empresas, gobiernos y la comunidad científica. La virtualización de máquinas ha permitido encapsular en un solo dispositivo físico múltiples instancias de sistemas operativos, permitiendo un menor consumo de energía gracias a la compartición de recursos. Debido a que estos recursos varían en el tiempo, se deben aplicar correcciones en la asignación de máquinas virtuales hacia otras máquinas físicas para garantizar los Objetivos de Nivel de Servicio (SLO).

El propósito principal de esta tesis es contribuir a los entornos Cloud en la mejora del consumo energético y de la Calidad de Servicio (QoS), por medio de los Acuerdos de Nivel de Servicio (SLA), mediante técnicas que permitan tomar el número adecuado de buenas decisiones. La planificación de recursos permite adaptarse a las necesidades y demandas de cada máquina física y virtual para mejorar el rendimiento general del sistema.

Realizando las asignaciones de tareas y migraciones de máquines virtuales adecuadas, se puede llegar a obtener centros de datos más estables y eficientes, requiriendo una menor supervisión y correcciones, garantizando una cantidad esencial de máquinas físicas activas funcionando correctamente y evitando la realización de acciones redundantes.

En esta tesis se ha tratado con dos tipos de entornos con cargas de trabajo reales. En primer lugar, en los entornos estáticos, se ha resuelto el Bin Packing Problem optimizando la energía y el tiempo de ejecución (makespan) mediante un algoritmo genético multiobjetivo (BLEMO). En el segundo problema, los entornos dinámicos, se han desarrollado diferentes propuestas. Se ha propuesto un algoritmo de selección de máquinas virtuales (WPSP) para reducir el número de migraciones y Violación de SLA, junto con un algoritmo de asignación de host (MDG) para reducir las comunicaciones entre hosts, optimizando el ancho de banda. Se ha combinado el uso de las Bandas de Bollinger con el framework Neural Prophet (BB+NeoPro) para generar

predicciones a más largo plazo, estabilizando el centro de datos y optimizando el número de migraciones, energía y Violación de SLA. Finalmente, se ha desarrollado una versión mejorada de BB+NeoPro combinando WPSP, BB y Facebook Prophet (WBF), probándola con diferentes cargas de trabajo del Cloud para validar su robustez.

Además, se ha extendido el simulador Cloudsim, creando MetaCloudsim, incorporando nuevas funcionalidades, técnicas, cargas de trabajo, algoritmos y herramientas.

El análisis de resultados muestra como las métricas analizadas obtienen beneficios sustanciales gracias a la exploración polivalente del espacio de búsqueda en el caso de entornos estáticos, y a la observación cuidadosa y adaptada de los datos disponibles en entornos dinámicos para una mejor toma de decisiones.

Resum

Des que la informàtica i Internet es van integrar en la nostra societat, s'ha requerit l'ús de grans centres de dades per tal de donar servei a clients, empreses, governs i la comunitat científica. La virtualització de màquines ha permés encapsular en un mateix dispositiu físic múltiples instàncies de sistemes operatius, permetent un menor consum d'energia gràcies a la compartició de recursos. Degut a que aquests recursos varien en el temps, s'han d'aplicar correccions en l'assignació de màquines virtuals cap a d'altres màquines físiques per tal de garantir els Objectius de Nivell de Servei (SLOs).

El propòsit principal d'aquesta tesis és contribuir als entorns Cloud en la millora del consum energètic i de la Qualitat de Servei (QoS), a través dels Acords de Nivell de Servei (SLA), mitjançant tècniques que permetin prendre el nombre adequat de bones decisions. La planificació de recursos permet adaptar-se a les necessitats i demandes de cada màquina física i virtual per tal de millorar el rendiment general del sistema.

Realitzant les assignacions de tasques i migracions de màquines virtuals adquades, es pot arribar a obtenir centres de dades més estables i eficients, requerint una menor supervisió i correccions, garantint un nombre escencial de màquines físiques actives funcionant correctament i evitar la realització d'accions redundants.

En aquesta tesis s'ha tractat amb dos tipus d'entorns amb workloads reals. Primerament, en els entorns estàtics, s'ha solucionat el Bin Packing Problem optimitzant l'energia i el temps de còmput (makespan) mitjançant un algorisme genètic multi-objectiu (BLEMO). En el segon problema, els entorns dinàmics, s'han desenvolupat diferents propostes. S'ha proposat un algorisme de selecció de màquines virtuals (WPSP) per tal de reduïr el nombre de migracions, energia, SLA Violation, juntament amb un algorisme d'assignació a host (MDG) per reduïr les comunicacions entre hosts, optimitzant el Bandwidth. S'ha combinat l'ús de les Bandes de Bollinger amb el framework Neural Prophet (BB+NeoPro) per tal de generar prediccions a més llarg termini, estabilitzant el centre de dades i optimitzant el nombre de migracions, energia i Violació de SLA. Finalment, s'ha desenvolupat una versió millorada

de BB+NeoPro combinant WPSP, BB i Facebook Prophet (WBF), provant-la amb diferents càrregues de treball del Cloud per provar la seva robustesa.

A més, s'ha extés el simulador Cloudsim, creant MetaCloudsim, incorporant noves funcionalitats, mètriques, cargues de treball, algorismes i eines.

L'anàlisi de resultats mostra com les mètriques analitzades obtenen millores substancials gràcies a l'exploració polivalent de l'espai de cerca en el cas dels entorns estàtics, i a l'observació acurada i adaptada de les dades disponibles en els entorns dinàmics, prendrent millors decisions.

Resumo

Desde que a computação e a Internet passaram a fazer parte da nossa sociedade, grandes Datacenters têm sido requisitados para atender clientes, empresas, governos e a comunidade científica. A virtualização de máquinas tornou possível encapsular várias instâncias de sistemas operacionais em um único dispositivo físico, permitindo menor consumo de energia no compartilhamento de recursos. Como esses requisitos de recursos variam ao longo do tempo, as correções na alocação de máquinas virtuais e outras máquinas físicas devem ser aplicadas para garantir os Objetivos de Nível de Serviço (SLOs).

A presente tese tem como principal objetivo contribuir para ambientes Cloud através da melhoria do consumo de energia e da Qualidade de Serviço (QoS), mediante o Service Level Agreement (SLA), através de técnicas que permitem executar as decisões corretas no momento correto. O planejamento de recursos permite a adaptação às necessidades e demandas de cada máquina física e virtual para melhorar o desempenho geral do sistema. Ao realizar atribuições otimizadas de tarefas e migrações de Máquinas Virtuais, os Datacenters tornam-se mais estáveis e eficientes, exigindo menos supervisão e correções, garantindo o indispensável número de máquinas físicas ativas funcionando corretamente e evitando a realização de ações redundantes.

Dois tipos de ambientes foram tratados durante esta tese. Em primeiro lugar, os ambientes estáticos foram enfocados, onde o Problema do Bin Packing foi resolvido para otimizar a energia e o makespan propondo um algoritmo genético multiobjetivo (BLEMO). Em seguida, os ambientes dinâmicos foram tratados, nos quais foram desenvolvidas diferentes propostas. Inicialmente, um algoritmo de seleção de máquina virtual (WPSP) foi proposto para reduzir o número de migrações e também a Violação de SLA. A proposta incluiu um algoritmo de alocação de VM para host (MDG) para reduzir o total de comunicações entre hosts e, em seguida, otimizar a largura de banda da rede. Em seguida, o uso de Bollinger Bands (BB) foi combinado com o framework NeuralProphet (BB+NeoPro) para gerar previsões de longo prazo, que permitem consolidar a VM para hospedar alocações, reduzindo o número de migrações, o consumo

de energia e a Violação de SLA. Além disso, uma versão melhorada do BB+NeoPro é proposta combinando WPSP, BB e Facebook Prophet (WBF). Esta proposta é testada com diferentes cargas de trabalho em Nuvem de vários provedores para validar sua robustez.

A análise dos resultados obtidos mostrou como todas as métricas avaliadas obtiveram benefícios substanciais graças à exploração multifuncional do espaço de busca no caso de ambientes estáticos, e a observação cuidadosa e adaptada dos dados disponíveis em ambientes dinâmicos que permitiram tomar melhores decisões.

> All models are wrong,
>
> but some are useful
>
> *George E.P. Box*

Acknowledgments

First I need to acknowledge the experiences lived with my tutors, Dr. Fernando Guirado and Dr. Josep L. Lérida, without them now I would be a completely different person. Besides research abilities, with them, I learned important soft skills necessary for life.

This thesis would not have been possible without the support of many people. All of them have contributed in one way or another to continue working. To force me to not work when it was not the time, to cheer me up and to guide me. To calm the mind and hear me when I require and also understand them when they require.

Thanks to my lab mates Jordi Bartolomé, Marc Solé, Úrsula Castillo, Dr. Eloi Gabaldón, Alba Lamas, Dr. Javier Valera and Carolina Sola for sharing time with me. With special mention to Dr. Daniel Gibert for being the best labmate and an example of an excellent researcher, Pol Llagostera for his cordiality and know-how, and Vitor Da Silva for his capacity to push people to be better.

During those years some professors allowed me to teach in their classes, thanks for the opportunity to Dr. Jordi Planes, Dr. Teresa Alsinet, Dr. Josep Argelich, Dr. Josep L. Lérida and Juan Manuel Gimeno. Moreover, thanks to Dr. Francesc Solsona and Dr. Fernando Cores for their exceptional support.

Thanks to my friends Roger, Jose and Jaume for their priceless friendship and loyalty.

Thanks to Ferran for the good times training and friendship.

Thanks to Gorka for his friendship and wise pieces of advice, as well as his compassion and professionalism.

Thanks to Thaïs and José Luís for their contagious happiness. Thanks to my gym mates to clear my mind with a smile, a back pat or, sometimes, a twisted knee.

Thanks to Marcel·lí for introducing me to programming, Josep Ramón and Gerard for making me enjoy Maths and Ms. Pepita for instilling in me the curiosity for knowledge.

Thanks to LleidaHack for creating great events that helped me to relax and to be more confident.

Thanks to Silvia for the good moments together, for making me reflect and be more aware.

During my doctoral stay in Sorocaba I met wonderful people, thanks to all for making me to see life from other perspectives. To my supervisor Dr. Fábio L. Verdi for his guidance; to Dr. Paulo Ditarso and André Beltrami for being the best roommates I will ever have; to Oswaldo, Christian, Cindy, Juan and the Orquestra Sinfônica for the nice moments. To Mari for her kindness and brightness, and her family, for welcoming me, to all, thanks for creating moments that have left a mark on me. Thanks for all.

Thanks to my parents for providing all the necessary and more to enable me to be here without expecting anything in return.

To those who are going to read this thesis, I hope it could help in your research.

To all people not mentioned here but deserves my thanks, to all of you, sorry for forgiving you.

To all the people I have not had the pleasure of meeting yet.

Contents

List of Figures

Chapter 1

Introduction

> Tot està per fer i tot és possible
>
> *Miquel Martí i Pol*

1.1 Context

Before the existence of Cloud Computing, users were only able to execute processes with the resources in their own physical machines, also called hosts. This generated multiple issues related to both performance and the waste of resources and energy. On the one hand, the vast majority of the time, the computational load was unable to use all of the device's capabilities, so these remained idle. On the other hand, in certain moments, the computing requirements exceeded the available resources, impeding the completion of tasks in the desired time, or even their execution.

Datacenters are an option for users to access those computing resources necessary to run their applications. The possibility of multiple users accessing datacenters offers an opportunity to amortise their computing resources by being able to share them among a large group of users. This form of sharing in turn poses great challenges related to the efficient management of computational resources, the energy consumption of these infrastructures and, above all, the ability to ensure the quality of service required by users in the execution of their applications.

The wide heterogeneity in the demand for computing resources by users has produced an evolution in the way in which datacenters offer their resources. Clusters of specialised computers, federated computing environments and GRID computing are some of these adaptations. Currently, the most widespread form is Cloud Computing.

Cloud Computing allows the execution of multiple completely isolated operative systems (OS) in the same physical device. Those virtualised OSs are called Virtual Machines (VMs). Thus, depending on the users' requirements, a variable amount of resources can be dynamically assigned. Multiple VMs can coexist on the same host, making full use of it.

Moreover, those VMs can be transferred from one host to another thanks to VM migrations. The demand for VMs varies over time and the processes running on them require a specific quantity of resources, such as power computation, memory, etc. Depending on the VM requirements and hosts availability, one host can collect VMs from other hosts, leading the latter into an idle state. In this mode, their energy consumption is up to 70% of their maximum peak at full performance [1, 2]. The opposite occurs when a VM require more resources than are available on the allocated host. Then, this VM can be migrated to a host that fulfils all its necessities. This may occur due to the sum of the maximum requirements of all the VMs in a host surpassing its capacity. This situation is not expected to happen usually because the VMs will not demand their maximum peak all the time. In situations with high resource demands, a rescheduling of the saturated hosts requires some decisions to be taken: which hosts are really overloaded, which VMs must be moved and which hosts will accept these.

Nowadays, the use of the Cloud has been democratised thanks to companies that provide these services through datacenters, large computing centers with thousands of hosts. These services can also be available through universities and research institutions, although their use may not be public. Depending on the services provided by these entities, users have different levels of control and supervision over the resources (PaaS, IaaS, SaaS). In general, the user only has to be concerned about the applications deployed in the Cloud and whether the resources allocated are sufficient.

Datacenter administrators must assign VMs to available hosts, and while these VMs are active, ensure they satisfy the requirements of the users. The administrators' challenge is to use the least number of hosts without VM performance issues in order to limit energy consumption.

Managing large amount of resources is not trivial. Both the number of VMs and their usage change every few minutes depending on the needs of the processes running. Not only is it important which resources are being consumed, but the placement of each VM also affects the network consumption, due to communications between VMs and VMs migrations. A balance between proximity (between hosts and VMs) and network consumption should be sought. Besides, choosing the right host for each VM is not a trivial decision, considering that not only is it necessary to provide enough resources so that the VM can guarantee the required user SLA, but it must also be able to ensure that these resources will be accessible in the near future.

In those situations in which the host's resources are saturated due to the demands of the VMs, the migration technique is a solution that allows the VMs to be reallocated to a different host. Thus, in addition to allowing the VM to satisfy its resources and guaranteeing the QoS, the workload of the source host is relieved, providing it with new opportunities to ensure QoS to the rest of VMs. Nevertheless, the migration process is not simple. There are multiple factors to consider in choosing the destination host, but also in selecting the VM that should be migrated. As mentioned above, the variable nature of VMs loads may mean that the best candidate at the present moment may not be so in the near future, or that the host with enough resources to satisfy the migrated VM may not be able to provide them shortly, after as this VM could require a greater amount of resources than destiny host can provide in a near future.

Another important challenge is related to datacenter energy consumption. Currently, the energy consumption of Cloud environments worldwide represents about 1.1-1.5% of the total energy consumed globally [3, 4]. Supplying this amount of energy involves power generation that release CO_2 into the atmosphere. Reducing energy consumption through better VM allocations will also make it possible to reduce the amount of CO_2 generated, allowing a more ecological and sustainable business model.

As shown above, the management of Cloud Computing environments is highly complex. That is why the author of this thesis considers that this kind of environment fits perfectly with the VUCA theory [5], a term derived from four different concepts: Volatility, Uncertainty, Complexity and Ambiguity [6, 7].

These four elements present the context in which organisations take into account their current and future state. For this, it is necessary to define a policy management plan to ensure the expected results. In the case of Cloud Computing environments these results are expected in terms of QoS, performance, energy consumption, host usage, etc.

In more detail, each VUCA component can be translated to the Cloud platform by the following ideas:

- Volatility: The computational resource requested by VMs changes constantly and fast, it being possible that Cloud users have undesirable performance goals that fall into poor SLA result.

- Uncertainty: The lack of predictability generates doubts about which actions will obtain the best outcome in the Cloud environment.

- Complexity: The number of possible solutions to the scheduling challenge corresponds to an NP-hard problem, making it impossible to reach the optimal solution in a reasonable time.

- Ambiguity: Due to the variable nature of the behaviour of virtual machines, it is necessary to obtain solutions that are consistent over time.

From the point of view of choosing a solution for the scheduling problem, there may be different criteria depending on the immediacy in the application of the solution and the results obtained. In a simple way, VUCA theory classifies the possible option that can be observed in Figure 1-1. This figure shows how different actions and solutions to a problem can be performed depending on the degree of awareness about the situation in the present and near future.

When an issue rises, some greedy algorithms (in red) can decide without looking beyond the present, thus proposing a quick fix in response to the current situation. This way of acting can lead to a spiral of additional and further actions. Finally, the solution should be obtained shortly after.

Another approach is based on more meditated algorithms (in yellow). In this case, more complex algorithms are used, requiring more time to react. In this way the solution is not obtained at the moment it appears but more sophisticated actions are proposed that can lead to a final solution in a medium period of time.

The VUCA concept also proposes the third kind of intervention (in green), resilient algorithms whose actions took more time to be effective after a premeditated wait to obtain more data and determine the cause-and-action proposal effectively. Part of this additional time is also required to execute much more complex algorithms. The lack of immediate decision is expected to grant better resolutions in the mid-term, requiring very few further actions and solving the issue efficiently despite the initial wait. This way of acting provides much more consolidated solutions.

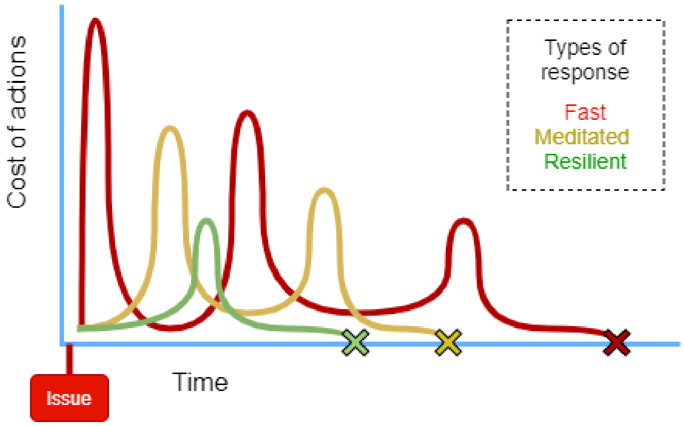

Figure 1-1: Response delivery time

The methods and proposals presented in this thesis have been carried out to try to achieve solutions that are mainly stable over time and with a minimum of future interventions.

1.2 Thesis Statement

The research group in which this PhD work has been carried out has extensive experience in scheduling computational resources for large workloads, having developed Mixed Integer Programming (MIP) methods, heuristics, meta-heuristics, genetic algorithms, and so on. In each of the works carried out, the objective has been related to the efficient allocation of resources to reduce the execution time of the load, the efficient use of the communication networks and even the reduction of energy consumption in the execution platform (clusters, multi-clusters, etc.).

This knowledge base has made it possible to define the beginning of this thesis, taking the methods already defined as a starting point and trying to extend these to Cloud platforms.

In Cloud datacenter management, the decisions taken during the VM migration process are focused on solving specific SLOs (Service-level objectives). Indirectly, those actions have additional costs that impact the QoS and energy consumption in the mid- and long-term. The rush to solve immediate problems with partial information can lead to subsequent reschedulings, adding redundant high-cost actions and degrading the VM interconnections of the network. By being aware of additional tracked metrics and the relation between them, without thinking in the immediate future, but in stable scenarios, based on counter-intuitive doings, Cloud datacenter managers can reduce the number of direct actions required without compromising the QoS and cutting energy consumption.

1.3 Hypothesis

The development of this thesis took into account the hypotheses stated below and that served to define the roadmap and actions to be carried out during its execution.

- **H1: The use of a Multi-Objective Genetic-Algorithm is able to obtain better makespan and energy results in HPC task-oriented Clouds.**

  In previous works, carried out within the GCD research group, it was shown that the use of multi-objective meta-heuristics based on genetic algorithms offer very good results for the scheduling process both from the point of view of makespan and reduction of energy consumption.

Our first hypothesis is that Cloud environments can benefit from this type of meta-heuristics for scheduling workloads that are traditionally present in the HPC field.

- **H2: The correct selection of VMs, evaluating the CPU load and network usage, can produce benefits by reducing the number of migrations.**

  The VM migration process in Cloud environments allows the available resources to be adapted to the needs of the workload. The proper choice of VMs should not only take into account the CPU resource but also the use of the network.

  This correct choice would result in an optimal allocation of VMs and a significant reduction in energy consumption.

- **H3: The use of predictions and technical analysis indicators provides new opportunities for optimising energy consumption and SLA.**

  It is considered that the efficient management of the resources should be carried out not only taking into account the current state of the system, both for the VMs and the hosts, but also considering their future situation.

  This assumption implies the analysis, testing and corroboration that the prediction tools are applicable to the scheduling process in Cloud environments and produce efficient results and new opportunities for optimisation.

- **H4: The application of both correct VMs selection and forecast techniques can produce great benefits in Cloud Scheduling.**

  Finally, it is corroborated that the joint use of the correct selection and prediction in the use of resources allows a powerful scheduling framework with great energy efficiency and good performance for the user to be defined.

In addition, it is considered that this proposal may be valid for use regardless of the type of workload in the Cloud environment.

1.4 Milestones

To achieve the aforementioned hypothesis, the following set of milestones that divide these hypotheses into more specific goals are proposed. These milestones are organised following a roadmap that allows us to learn and overcome the complexity of the problem:

- **M0: GCD Research group overview and exhaustive study of the state of the art in the field of Scheduling applied to Distributed Environments.**

  The GCD research group has extensive experience in the field of resource management and optimisation in distributed computing environments. The first task is to know the initial background that will shape this thesis. Next, a detailed analysis of the state of the art in the literature must be carried out. At the same time, the tools that will be the basis for the experimental development must be defined.

- **M1: Enhancement and new development tools for the experimental study.**

  The experimental study requires the use of tools which, in some cases, are not prepared to generate the required data. An important task in this thesis is to ensure the adequacy of these tools, as well as the creation of any new ones that may be required.

- **M2: Design of a Multi-objective metaheuristic method for scheduling optimisation applied on Cloud Computing.**

  The initial point of this thesis is the multi-objective genetic algorithms applied to highly distributed computing environments that have been developed in the

GCD research group. In this milestone, a meta-heuristic will be defined and developed, based on the group expertise, that allows the scheduling of applications in Cloud environments to be optimised.

- **M3: Identification of the most relevant factors affecting host saturation and performance in Cloud Computing.**

  Due to the high variability in the computational load present in Cloud environments, the analysis and identification of the most relevant parameters that influence the saturation of the hosts in the Cloud infrastructure is required. This analysis will serve as the basis for the development of new methods for optimising the Cloud platform.

- **M4: Optimisation of the VM migration process in Cloud Computing.**

  In Cloud environments, the migration of the VMs assigned to the hosts is one of the most important tools to ensure both optimal performance in the execution of the services, and to avoid the saturation of the hosts. Thus, new methods will be created for efficient migration of VMs according to the chosen performance criteria.

- **M5: Definition of new energy-aware scheduling methods in Cloud Computing.**

  Currently, one of the most important problems facing our society is the need for decarbonisation and therefore the reduction of energy consumption. In this sense, the efficient use of resources bearing in mind the energy cost is an urgent necessity. In this milestone, the adaptation of the proposals with a focus on energy optimisation is proposed.

- **M6: Scheduling optimisation based on forecasting frameworks in Cloud Computing.**

  The efficient management of computational resources requires not only that any decision must be adequate when it is produced, but it should also be valid and consolidated over time. Under this premise, this milestone adds the dimension of predicting the behaviour of VMs and hosts in the resource management process with the idea of obtaining greater efficiency in the use of resources.

1.5 Research Methodology

The methodology that has been followed in this thesis is based on the hypothetical-deductive method proposed by Adrion [8]. This proposal applies the classic scientific method, keeping in mind that there is a component of transversality between scientific fields and engineering in Computer Science. In this way the research is divided into four parts, which can be repeated depending on their results:

1. **Observe existing solutions.**
   This part consists of an in-depth analysis of the related work. This is necessary in order to avoid working on a previously solved problem. Moreover, the study of other scientific fields can provide new ideas to be applied in the field. The models already proposed about the Cloud infrastructure, migration process, energy consumption, existing workloads, etc, were analysed.

2. **Propose better solutions.**
   With the extensive knowledge acquired during the study of the related work, existing solutions are analysed to determine new innovative proposals that allow going beyond the results obtained by the literature.

3. **Build or develop new solutions**
   In this part, new scheduling techniques were proposed and implemented. When problems appear, step 2 is repeated to find a new solution. This step can also lead us to repeat step 1 to analyse in the literature how to solve a specific problem.

4. **Measure and analyse the new solution**
   Finally, the solutions are tested and evaluated in comparison with the proposals

in the literature. If the results are not good enough, the previous steps are repeated until the solutions are improved.

1.6 Organisation of the Thesis

The present PhD work is arranged as follows:

- **Chapter 1 - Introduction**, establishes the basis for the Cloud environments, in terms of the main goal of the thesis, defining the main hypotheses and milestones to reach.
- **Chapter 2 - Background**, goes deeper into the core concepts of Cloud optimisation techniques, describing the procedure for migrating VMs, the different kinds of algorithms and statistical methods studied in the papers presented below.
- **Chapter 3 - Papers**, offers a resume of the most relevant publications that make up the research, presenting the proposals and results obtained for each one.
- **Chapter 4 - General Conclusions and Future Work**, extracts the lessons learned about how Cloud environments react to the techniques studied and developed, and how these can be exploited by other researchers. Finally, some future work that continues this thesis is presented.

Chapter 2

Background

> Everything we hear is an opinion, not a fact. Everything we see is a perspective, not the truth
>
> *Marcus Aurelius*

This chapter introduces the reader into Cloud Computing concepts that will facilitate the comprehension of Chapter 3. These include the computational models used, the workloads that were utilised in the experimental study, the VM optimisation process and the techniques, and a statistical analysis of time series.

2.1 Models

The usage of a Cloud environment can be determined by a main characteristic, the level of completeness of the executed tasks. If the tasks are well defined, with a specific number of operations to complete them, the system is defined as offline. On the contrary, if the tasks run indefinitely, with variations on their resource demand, the system becomes online.

During the progression of this thesis, both offline and online environments were dealt with. The former as the natural evolution of previous research done in the author's research group, and the latter step, focused on the online environment, which is much more closely related to Cloud Computing platforms.

Both models are summarised in the following sections.

2.1.1 Offline model

The task-oriented (or offline) model consists of a set of finite tasks (cloudlets) that must be executed in a Cloud datacenter, assigning the cloudlets to pre-existing VMs in running hosts [9, 10].

Some of the challenges of this kind of scenario are:

- Makespan: Finding the optimum VMs to hosts allocation that allows all the tasks to be completed in the minimum possible time (makespan). This is determined by the difference from the finish time of the last task and the starting time of the first one.

- Energy consumption: To find the best mapping of VMs to hosts in order to reduce the amount of energy consumed.

- Wastage of resources: The efficiency of the system is determined by the occupation of resources by the active devices. The more resources wasted, the less the efficiency obtained. Thus, the goal is to obtain the best performance (makespan, energy) when using the minimum amount of resources.

- Decision time: Once tasks are received, the required time to decide what to do in order to obtain the best performance. The decision time tends to be orders of magnitude lower than the task execution time. However, in such a computing environment, the huge number of tasks makes a relevant value to take into consideration.

For the offline model, the computational model that determines the task execution time and the energy model will be defined, this being the one that allows the amount of energy in the execution process to be evaluated.

Computation model

A datacenter D is made up of a set of hosts H, H being $H = H_1, H_2, ..., H_{|H|}$, and receives a bulk of cloudlets C, C being $C = C_1, C_2, ..., C_{|C|}$, to be executed in the hosts. Each host has a number of CPU cores. Each core can execute a number of Mega Instructions Per Second (MIPS).

Each cloudlet has a number of Mega Instructions (MI, millions of instructions) to be completed. One or more CPU cores can be required. The time a host spends to complete a cloudlet is $C_{i_t} = \frac{C_{i_{MI}}}{H_{j_{MIPS}}}$, where C_i is calculated by H_j.

The makespan (M) is defined as the time elapsed from the submission of the first cloudlet to the finalisation of the last in the whole workload, as expressed by Equation 2.1.

$$M = \max_{i \in \mathcal{CL}}(Finishtime_i) - \min_{j \in \mathcal{CL}}(Starttime_j) \tag{2.1}$$

where $\mathcal{CL}$ is the set of cloudlets that represent the whole workload.

Energy Model

The energy consumption of the whole set of tasks is defined by the power consumption of the running hosts and the makespan time where they are being calculated or waiting to enter into the execution state. The host is considered to be idle when all the allocated VMs have executed their cloudlets completely and these do not depend on other VMs still running.

Under the previous statement, the energy consumption for each core in a host can be defined by Equation 2.2.

$$E(c_x) = \int_0^M E_{comp}(c_x, t) + E_{idle}(c_x, t)dt \tag{2.2}$$

where E_{comp} and E_{idle} are the energy consumed during the computation and the idle period, respectively, by core c_x in the time period t. Assuming $E(c_x)$ as the energy consumption by core c_x, the total energy consumption (TE) can be calculated by Equation 2.3.

$$TE = \sum_{c_x \in H} E(c_x) \quad \forall H \in \ Hosts \tag{2.3}$$

$Hosts$ being the list of physical servers used to host the VMs. In this model, the energy consumption only depends on the CPU cores.

2.1.2 Online model

In the online model, the datacenter is continually running end-less tasks, i.e., applications such as websites, databases services and background tasks ready to compute and serve data [11, 12].

A datacenter, D, contains a set of hosts H, being $H = H_1, H_2, ..., H_{|H|}$, where $|H| = n$ and a set of switches $S = S_1, S_2, ..., S_{|S|}$, where $|S| = o$, forms the set of physical entities $E = H, S$. There is a set of VMs $V = V_1, V_2, ..., V_{|V|}$, where $|V| = m$.

Each VM is allocated to a unique host if it is not migrating (live migration process). We assume that during the migration process any VM consumes 90% of the initial CPU usage and 10% from the target host.

In these environments, cloudlets are placed in VMs, and their resource requirements can be variable during their execution. In a specific moment t, a VM requests an amount of CPU load (MIPS) and consumes BW for each one of its links.

Some of the main objectives in this scenario are the following:

- To reduce SLA Violations: When the VMs in a host request more MIPS than it has available, an SLA Violation occurs. It is important to avoid, or at least to reduce as far as possible, this criterion to ensure that VMs, and with this, the final users, obtain the required QoS.

- Network usage: This is related to the communications between VMs and also the VMs in case they are migrating between hosts. The overload in the network can produce high latencies and, for the VMs, low capacity to respond to any demand.

- Energy consumption: The number of hosts and their resource usage determines the amount of the energy consumed by the datacenter.

The computational and energy model for the offline environment is defined in next subsections.

Computing model

At every instant of time t, VMs are requesting a specific number of MIPS in terms of the CPU computational capacity. Every host h can provide h_{total}^{MIPS} MIPS for their current $h_k(t)$ VMs. If a VM is migrating, it is present in the origin and target hosts at the same time, but calculations are split between them, as shown in Equation 2.5. If a VM is running in a host and is not migrating, the full current demand is provided. However, if the total MIPS requested by the VMs of a host surpass the host's capacity, the total MIPS are split proportionally between each VM, generating an SLA Violation in each VM.

Equation 2.4 calculates the number of MIPS executed by the hosts in function of the MIPS requested by VMs. Where $MIPS\_VM_i^k(t)$ is the current CPU demand of the VM i in host k at the moment t. This value varies between 0 and the maximum number of MIPS that the VM has, in function of the assigned cloudlet. In this thesis cloudlets are defined by the workload traces under study. These are presented in Section 2.2.

$$DC_{MIPS} = \sum_{h=1}^{H} \int_{0}^{T} min \left(\sum_{i=1}^{h_k(t)} MIPS\_VM_i^k(t) \cdot STATE\_VM_i^k(t), h_h^{total^{MIPS}}(t) \right) \tag{2.4}$$

The different states for a VM are defined as follows:

$$STATE\_VM(t) \begin{cases} 0.9, & VM\ migrating\ from\ origin\ host \\ 0.1, & VM\ migrating\ from\ target\ host \\ 1, & VM\ not\ migrating \end{cases} \tag{2.5}$$

Network model

The topology of a datacenter D conforms a connected graph. Each host is connected to one switch, each switch to a set of switches and hosts. Each connection, called link, L, communicates two devices, one of them a switch and the other a host or a switch. A limited number of BW (bytes per second) can travel across the link. If more BW is required to pass, the BW exceeded is discarded.

Hosts are interconnected with a set of wired connections, $L = L_1, L_2, ..., L_{|L|}$, with other end-hosts through intermediate switches, $S = S_1, S_2, ..., S_{|S|}$.

A path P is the ordered list of links that connect two devices. Physical paths are formed with physical links, whose ends are hosts. Logical paths are made up of logical links, whose ends are VMs. A logical path can be broken down into three parts: the interconnection between a VM and its origin Host, the physical path between hosts, made up of physical wires, and the interconnection with a target Host and a VM which is communicating with the VM of origin. The same link can be used by multiple paths, combining their BW usage. If the sum of BW surpasses the BW capacity of the link, the link is saturated.

During the execution of a datacenter, VMs can be transferred from one host to another using the existing links. Moreover, each VM can have a set of communicating VMs which interchange information. The network routing system usually applies Dijkstra's algorithm [13] to determine how paths are conformed.

Energy model

In this thesis, the energy model evolved from the most basic energy model, found in the CloudSim simulator, to a fine-grained energy model that involves almost all the elements in the Cloud datacenter. The energy model proposal describes how the usage of the entities of a datacenter is related to the corresponding energy consumption. Even datacenters are, at essence, buildings with an enormous number of servers, the whole infrastructure (including the personnel) is focused on serving these. That includes cooling systems, electricity, human resources and so on. This kind of meta-infrastructure is not included in the present energy model, only the elements related to the hosts and the networking being taken into consideration. Next, the full energy model developed is presented.

Sarji et al. [14] tested various real scenarios to characterise the Host energy consumption during the start-up and shutdown processes. Outin et al. in [15] characterised the energy consumption of a migration based on the information volume that must be sent through the network. In the present work, the authors adopted the formulation of these previous works to take into account the following energy costs:

- E^i_{on}: When a VM is sent to a powered-off Host i, the target host needs some time to become active. A powered-off host needs 154.2 seconds and consumes 43020 Joules to be ready to receive VMs. The energy spent on start-up operations for Host i can be calculated by equation 2.6. Let $n^i_{startups}$ be the number of start-up operations for Host i.

$$E^i_{on} = 43020J * n^i_{startups} \tag{2.6}$$

- E^i_{off}: When an active Host i has no more VMs, the host is shutdown, taking 28.8 seconds and 5560 Joules. The energy consumption on shutdown operations for a Host i can be expressed by equation 2.7. Let $n^i_{power-off}$ be the number of power-off operations for Host i.

$$E^i_{off} = 5560J * n^i_{power-off} \tag{2.7}$$

- E^i_{mig}: The energy consumption produced by a VM migration k can be approximated using equation 2.8, based on the data volume sent through the network (V^k_{mig}), expressed in MBytes. This energy consumption impacts both the origin and target hosts involved in the migration process equally. Therefore, the energy consumption due to migrations in Host i, can be expressed by equation 2.9, as the energy consumption for all migrations k with origin or destination in Host i. Extending the formula to include each network hop, the energy expended by the hosts and the intermediate switches is obtained, $E_{mig}+$, where

h_o is the origin host, h_t, the target host, and n_{hops} the number of intermediate hops+1.

$$E^k_{mig} = 4.096 * V^k_{mig} + 20.165 \tag{2.8}$$

$$E^i_{mig} = \sum_{1}^{k} 4.096 * V^k_{mig} + 20.165 \tag{2.9}$$

$$E_{mig+} = \sum_{1}^{k} 4.096 * n_{hops}(h_o, h_t) * V^k_{mig} + 20.165 \tag{2.10}$$

- E^i_{host}: The energy consumption by Host i during the active period is expressed by the variable E^i_{host} and it is reported by CloudSim.

- $E_{VM_{com}}$: The energy consumption derived from the VM communications in hosts and switches. Instead of calculating only the bytes in and out of hosts, full paths between pairs of host endpoints are obtained. The formula is an adaptation of equation 2.10 VMs being present instead of hosts. Thus, equation 2.11 shows how to obtain the energy used in VM communications, k being the number of communications, V^k_{com} the data transferred in a communication, vm^k_o and vm^k_t the origin and target VMs of a communication, and $host(vm)$ the host of the specified VM.

$$E_{VM_{com}}+ = \sum_{1}^{k} 4.096 * n_{hops}(host(vm^k_o), host(vm^k_t) * V^k_{com} + 20.165 \tag{2.11}$$

After defining the different components of the energy model, the final energy formula is presented in Equation 2.12, expressed in KWh and representing the energy used by the whole datacenter:

$$E = E_{host} + E_{on} + E_{off} + E_{mig+} + E_{VM_{com}+} \tag{2.12}$$

2.2 Workloads

In this thesis, the experimental study was carried out through simulation, using the CloudSim simulator, and treating different workloads obtained from real datacenters. This allowed the proposals for multiple workloads and different situations to be validated.

A formal definition of a workload can be the next: the set of data that allows the modelisation of a behaviour. Specifically, in the Cloud, they offer information about the quantity of resources that a set of tasks requests during its execution.

A workload can be mainly classified by its purpose, becoming a static or dynamic workload as shown in Figure 2-1.

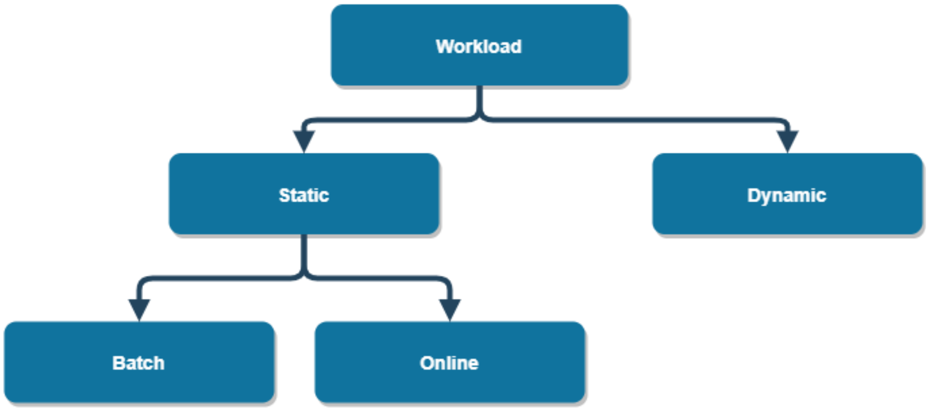

Figure 2-1: Workload classification

The initial steps of the present thesis were based on static workloads. Next, the thesis evolved towards dynamic workloads. That is why both kinds of workload are commented on below for each item in the previous classification.

Static workloads

A static workload is a set of tasks with a defined quantity of resource demand to be completed. Depending on the availability of the tasks at start-up, they can be classified into two approaches:

- Batch: The system is empty at the startup. Then, all the tasks enter it with all the requirements and resource demands present. For this workload, the scheduling process can be treated as the Knapsack problem.

- Online: Subsets of the tasks enter into the system as time goes on. This behaviour can be modelised as a set of overlapping offline workloads. The main issue of those task plannings is the lack of knowledge about the future requirements of the tasks that have not yet arrived, which causes reschedulings of the current tasks in the system.

The moment a task appears, its resource requirements, i.e. the amount of MIPS to be completed, are fully known. With this, the scheduling process can simulate and calculate the moment when the task finishes.

In Cloud environments, those tasks are called cloudlets. Cloudlets are allocated on VMs, which fulfil the necessities of the cloudlets. Finally, in turn, the VMs request this number of MIPS from the assigned host.

Traces

At the beginning of this thesis, static type workloads were used. These were obtained from the Parallel Workloads Archive page [16], whose author is Dror G. Feitelson. Each trace is composed of batch jobs from Grid environments, indicating the number of tasks and the number of MIPS required to complete them [17]. Specifically, the ones used were CEA-Curie, HPC2N and Sandia-Ross.

Dynamic workloads

A dynamic workload consists of a set of tasks whose requirements change over time with a non-defined finalisation time. The reason the requirements change is the variable kind of processes that are being executed.

The cloudlets of dynamic workloads are each assigned to one VM, defining how those VMs behave and requesting resources for their hosts. In this context, and in a practical way, a cloudlet and a VM are the same.

Workload	Trace	# Virtual machines	Duration	Characteristics											
				CPU				RAM			IO			Network	
				# cores	MIPS capacity	Usage	%	Memory capacity	Usage	%	% read	% write	HDD	Received	Transmitted
PlanetLab	20110303	1052	1 day				✓								
	20110306	898													
	20110309	1061													
	20110322	1516													
	20110325	1078													
	20110403	1463													
	20110409	1358													
	20110411	1233													
	20110412	1054													
	20110420	1033													
Materna	trace1	521	30 days	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	trace2	527	31 days												
	trace3	547	36 days												
Alibaba	2017 (server usage)	1310	12 hours				✓			✓	✓(join)				✓
	2018	36212	8 days												
Azure	2017	2013767	30 days (each VM, variable)				✓								
	2019	2695548													

Table 2.1: Dynamic Workloads comparative

There are multiple dynamic workloads available from research centres and companies that have released them publicly. The next section presents the dynamic workloads that were used during the present thesis, and Figure 2.1 shows their main attributes.

Next, each of the workloads is presented.

PlanetLab

PlanetLab workload is the default dynamic set of traces that comes with CloudSim. The data was collected in an infrastructure composed of a network with 1353 nodes, split into 717 locations around 48 countries as an open platform to test global deployment services [18]. During 2002, 10 days of CPU data were collected. The VMs CPU load tends to be high in this workload and they show a wide dispersion in their necessities.

PlanetLab VMs exhibit a high variability of resources demand, passing from high to low requirements in short periods of time. This behaviour may cause many VM migrations that can be correct at the same moment, but easily become erroneous in the near future.

Alibaba

Alibaba Cloud [19] is a subsidiary of Alibaba Group, which provides Cloud services such as e-commerce, elastic computing, container management, HPC, data storage and IoT. Alibaba Cluster Trace Program [20] provides researchers with production data related to their Cloud entities. The traces offered are related to multiple topics. The 2017 and 2018 traces are centered on VMs [21, 22], the ones from 2020 are about GPUs [23], and 2021, microservices [24].

The Alibaba workload has the VMs with the highest CPU demand and also exhibiting stable VM behaviour. The most characteristic trait of this workload is that most of its VMs follow a similar pattern. Thus, when there are variations or stagnancy, all VMs are similarly affected.

Materna

Materna [25] is an IT holding company focused on the corporate digital transformation. Between November 2015 and February 2016, three sets of traces were collected [26] as part of the FederatedCloudsim project [27], corresponding to one month. Each trace was composed of more than 500 VMs.

This workload is mainly characterised by low VM CPU usage, dispersion and accumulated difference with a very stable processing scenario during the simulation.

Azure

The Azure ecosystem [28], managed by Microsoft, provides a huge range of Cloud solutions for all kinds of companies and Microsoft products. These includes VM virtualisation, monitoring, storage, databases, DevOps solutions, IoT and Machine Learning, among others.

The Azure Public Dataset [29] is a collection of traces obtained over multiple periods of time and available to the academic community. The traces from 2017 and 2019 are related with VMs and packing algorithms. Those from 2020 and 2021 collect Azure Functions Blob Accesses and Function Invocations for serverless applications.

Azure has a medium CPU usage but exhibits a high accumulated difference in the half the VMs.

Network workloads

Some of the previous traces contain information about the input and output communications in VMs, the throughput and Mbps used to communicate with other devices or the Internet. It is important to take into consideration that not only is it necessary to know the network throughput over time, but also the fact that a device receiving information implies another sending it. Due to the migration process, the VMs exchanging data cannot be stored statically. Thus, only the throughput can be stored, but it is necessary that the network simulation be consistent during all the simulation. Any interaction between two VMs must be present in both of them, one as a sender and the other as the receiver.

For those experiments that require network interactions between VMs in this thesis, sin-cyclostationary network traces were generated in order to offer the required scenarios realistic data interaction. Figure 2-2 shows a sample of this interaction during the process, where the network usage is presented for all hosts in the simulation.

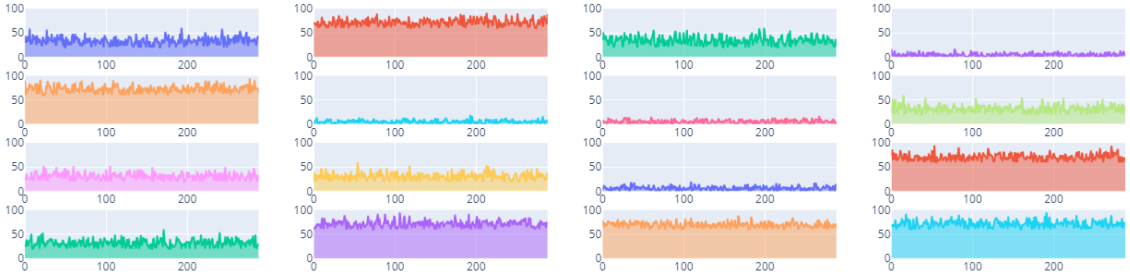

Figure 2-2: Network Workloads sample

2.3 Task Scheduling Problem

The assignation of batch tasks in a Cloud datacenter was a classic problem even before Cloud Computing become popular. Grid and multi-cluster environment faced similar challenges. Abstracting the problem, it operates as the Bin Packing Problem (BPP), where a set of elements with different numerical characteristics must be assigned to entities that can afford them. Specifically, in the present dissertation, cloudlets with a defined number of MI are assigned to the VMs that must execute them, with the calculation of MIPS necessities and the associated energy cost. There are many papers in the literature related to Task Scheduling solved with many varied approaches, from heuristics [30] to much more refined meta-heuristics [31] or even Mixed Integer Programming models [32]. There is a brief summary below of some of the proposals in the literature applied to Cloud Computing.

One of the optimisation research lines proposed the use of Exact methods [33, 34]. However, although the problem is NP-Hard, these do not scale properly. As a task prioritisation strategy, Agarwal et al. [35] proposed a cloudlet ranking based on bandwidth, memory and hard-disk size. A variation of the classic Min-min algorithm named *Enhanced Load Balanced Min-Min* scheduling algorithm, was suggested by Patel et al. [36]. This is based on optimising the makespan and resource utilisation selecting the tasks with maximum completion time and with proper assignation to the optimal resource.

Another approach followed by many researchers proposes the use of nature-inspired algorithms, such as Evolutionary Algorithms, due to their capacity to discover innovative solutions based on stochastic steps. An Evolutionary Algorithm (EA) is a search heuristic whose objective is to find near-optimal solutions inspired by nature-based behaviour through a search space. Usually, solutions to real-world problems are forced to optimise multiple fronts in order to model a true environment, these being Multi Objective Evolutionary Algorithms (MOEA) [37].

Specifically, Genetic Algorithms (GA) start with an initial random population composed of individuals, each one representing a solution, a scheduling in the case of the Bin Packing Problem over a bulk of tasks [38, 39]. The properties that identify each of these individuals are the chromosomes. Like living beings, GA algorithms evolve in higher quality, or almost, diverse, individuals over generations, inheriting the main characteristics from their precursors and making modifications to the individuals' chromosomes.

Moreover, there are other EAs based on more abstract concepts such as Differential Evolution (DE), similar to GA substituting chromosomes for a vector of real numbers and combining them one by one among the current population, and Simulated Annealing (SA) [40], which imitates how metal cools down, going from macro searches to fine-grained scans.

There are notable alternatives to GA under the domain of EA. Most of them are inspired by how animal herds become nearly a unique thinking entity, a swarm intelligence. There are the cases of Particle Swarm Optimisation (PSO) [41], based on the movement of flocks of birds and their internal hierarchies to decide the trend of the rest of the birds, Ant Colony Optimisation (ACO) [42], specialised in path optimisation thanks to ant pheromones, and ABC (Artificial Bee Colony), assigning different roles to bees to collaborate in the search for food sources.

As a notable GA contribution, in [43, 44], Cocaña et al. used NSGA-II algorithm and fuzzy rules to develop the EECluster method over HPC clusters.

Finally, it is worth mentioning that Saborido et al. [39] proposed the Global WASF-GA methods, which is able to approximate the Pareto front for multiple objectives. This method was used as the core for the GA implemented by the first main proposal in this thesis, BLEMO [45].

2.4 VM Migration Problem

This section presents the basis for understanding how datacenters balance the VM demand among the necessary hosts. Also discussed is the techniques that is the basis of this thesis in order to reach the aforementioned hypotheses and milestones.

2.4.1 Initial Setup and action plan

In order to clarify the VM migration process clearly it is important to take into consideration the migration starting point that enable the whole process.

Thus, from an arbitrary moment in the runtime of a datacenter, two rivals are competing for the computing resources. On one hand, hosts will try to be as relaxed as possible about guaranteeing the amount of resources requested by their allocated VMs. On the other hand, the VMs want all their petitions to be granted.

Thus, at any moment, some of the accumulated CPU requirements form the allocated VMs exceed the capacity of their host. This can be caused by several circumstances, but some scheduling decision should be taken.

Inspired in the legal and financial covenants, two different options can be adopted:

- *Positive covenant (doer)*: A decision is scheduled to execute an action, in this case a VM migration to alleviate the stressed host and also to assign the required resources to the VM. Thus, two hosts will exchange data through the network the target being the one that will acquire the responsibilities of the origin host. The origin host is relieved of that burden. This kind of covenant can fall onto greedy behaviours based on short term solutions that may cause further corrective actions.

- *Negative covenant (no-doer)*: A decision is actively forbidden, no actions are performed, forcing a host to maintain the burden even if there are saturations. This is a more conservative approach focused on long-term execution, waiting for the precise moment to perform positive covenants, and avoiding them if they are not really necessary.

The regularisation of covenants is parameterised by the quantity of bond violations occurred, in other words, in this context, the number of SLA violations. The datacenter must be aware of the saturation level of each host, taking the necessary measures to solve these saturations. If too many bond violations occur, the current negative covenants will be relaxed, allowing positive ones. On the contrary, if the system is able to maintain stability, or at the most, controlled saturations, negative covenants will block unnecessary VM migrations.

2.4.2 Migration decision steps

Prior to the main core of this section, the three main host states must be defined:

- *Correct balancing*: The VMs and host match correctly their resource demand, for now no migrations are required.

- *Oversaturation*: The demand is over the expected. Some VMs must be migrated to other hosts to guarantee the demand.

- *Underutilisation*: The demand is under a defined threshold. There is the possibility of moving all the VMs to other hosts, powering-off the current host.

Throughout operation of a datacenter, the hosts will be oscillating between the states presented above. To solve potential host over- and under-utilisations, a classic modular chained set of techniques to stabilise a datacenter is presented.

When it is decided that the migration process must be carried out, some steps are performed following the classic workflow depicted in Figure 2-3. This workflow is composed by four main steps.

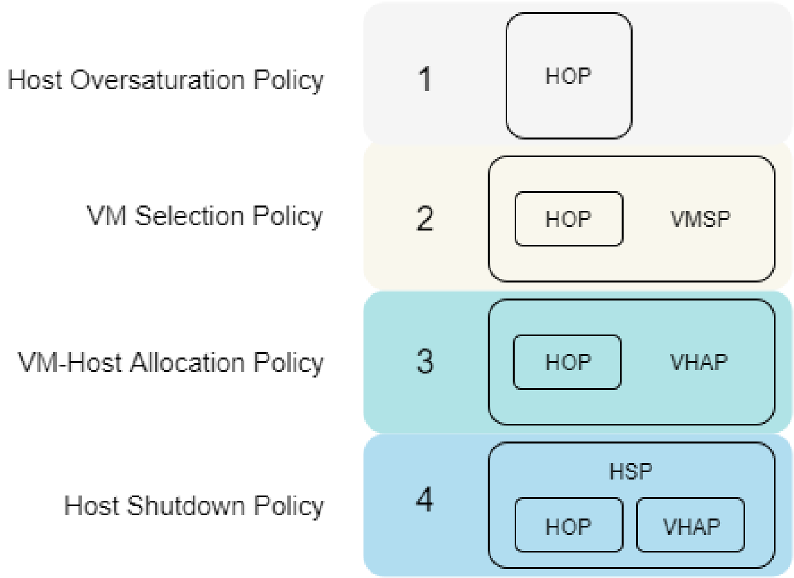

Figure 2-3: VM migration process

1. *Host Oversaturation Policy* (HOP): The host oversaturation algorithm checks the host status in each period of time and, in function of a defined criterion, classifies which hosts are saturated or non-saturated.

2. *VM Selection Policy* (VMSP): Once the saturated hosts are identified, the next step selects a set of VMs for each saturated host, choosing VMs one by one, until the host changes its status to non-saturated. This step requires the use of the previous one for each selected VM to check whether the host is saturated or not.

3. *VM-Host Allocation Policy* (VHAP): Once it is known which VMs should be migrated, the non-saturated hosts will be eligible objectives for migrating the selected VMs from the saturated hosts. Once again, the HOP technique is in charge of deciding when a potential match between a VM and a host does not cause oversaturation. It must be taken into account that in this step, it could be possible to power-on a new host that could be power-off because of the necessity for new computational resources.

4. *Host Shutdown Policy* (HSP): This last step allows the datacenter to stop growing uncontrollably by opening powered-off hosts. The usual procedure is to sort the hosts upwardly by their resource utilisation using a defined criterion. Those hosts with very low assigned workloads become candidates to be powered off just in case any other host can accommodate this workload. This compaction method allows the number of running hosts to be reduced, which then reduces the total energy consumption. The VHAP step assisted by the HOP one is used again for each potential host to be powered off. It is not necessary to apply the VMSP step because all the VMs in the host must be migrated.

Once all the previous steps are executed, a set of migrations is generated. The datacenter must trigger the migrations being careful not to saturate the local network and the Network Interface Card (NIC) of the hosts. Hence, the migrations should be performed gradually.

After the completion of all the VM migrations, the system should be stable and compacted. The whole process is repeated each time any VM demand again destabilises its host.

As a standard, most of the traces obtained store VM and/or host information every 5 minutes. That means that, between two instants, there is an interpolation of data from one to other. Moreover, migrations are performed at least every 5 minutes. By doing migrations at this rate, the algorithms that analyse historical values obtain a constantly mutated scenario that becomes difficult to control.

For this reason, in the present thesis, the migration rate is set to 30 minutes, allowing the algorithms almost 6 timestamps to analyse the environment without changes in the VM-host mapping, following the no-doer covenant. This decision affects the number of migrations performed, influencing the rest of the metrics. However, it is important to emphasise that must be a pre-period to know the behaviour of the datacenter, and a post-period observing the decisions made. Otherwise, the algorithms will take hasty decisions due to the lack of feedback.

2.5 VM Selection policies

As mentioned above, the second step in the VM migration process is determinant for further steps. Selecting the right VMs from oversaturated hosts, they will return to a stable situation.

The heuristic proposed by the author in [45, 46] utilises Pearson's Correlation Coefficient to correlate the CPU and network usage of the VMs in relation with their hosts, the main premise being that the VMs with direct resource correlations are the ones that cause saturations to their hosts.

Thus, in [47] the method was improved by adding the correlation weight, h-index, to the heuristic formula. This weight is the ratio between the resource demand of a VM and the total resources requested from the host. The combination of the Pearson Correlation determines the influence of an VM over its host.

Different methods for selecting VMs for diverse purposes can be found in the literature. Some techniques also use correlation methods. Choudhary et al. [48] employed the Spearman's Rank Correlation Coefficient for an optimal selection of VMs using the latest workload and datacenter resource availability, reducing the energy consumption without penalising the SLA compared with a random VM selection.

Using Pearson Correlation Coefficient, Moghaddam et al. [49] optimised the energy consumption and SLA correlating the VMs' CPU utilisation with their co-hosted VMs. Sun et al. [50] took a similar approach to correlations, using them in multiple datacenters, finding VMs that correlate with each other. Groups of VMs are migrated taking into account the necessary bandwidth and routing the whole batch, reducing the remapping cost and the time the VMs are migrating and in a downtime state.

Furthermore, there are alternative methods following other philosophies. For example, combining the VM selection method with other steps. Thus, Buanga et al. [51] used Pearson Correlation in the VM placement step, taking into account CPU, RAM and bandwidth over PlanetLab traces using CloudSim and realistic hosts from Amazon EC2. Thus they minimised SLA Violations and the number of migrations.

What differs our proposals from other techniques is the relation between both correlations, CPU and Network, applied by the heuristic. The WPSP method selects the VMs with the most influential CPU loads and also with fewer host communications to prevent the generation of CPU and network saturation.

2.6 VM-Host allocation policies

In this migration step, the author proposed the use of Neural Network Forecasting methods to predict the resource demand. Moreover, as a pre-filter, Bollinger Bands were applied to the original timeseries to obtain a long-term trend. With this, it is possible to avoid outliers due to saturation and also under-utilisation. The combination of the proposed forecasting techniques was improved with the addition of the WPSP method presented above. This allows a curated selection of VMs to be obtained based on the CPU and network correlated with the host status. As a result, the number of migrations can be diminished drastically, impacting the network utilisation, and hence, the energy consumption, directly. Furthermore, this proposal obtained a SLA Violation optimisation thanks to robust VM consolidation decisions.

The following paragraphs present a detailed compilation of methods in the literature that inspired the author's proposal.

Beloglazov et al. in [52] proposed a set of heuristic techniques for the selection of the VMs to be migrated and the destination Hosts. The experiment results demonstrated that there are no significant improvements in terms of energy consumption and the number of migrations. However, the use of policies that try to minimise the number of migrations provides the best energy savings with the fewest SLA violations.

Gupta et al. in [53] presented a maximisation of the resource host usage during the VM placement using a resource usage factor. The objective was to minimise power consumption. However, SLA violations and VM migrations increased due to the hosts being frequently overloaded.

Minarolli et al. in [54] presented a set of methods to detect over- and under-loaded hosts by applying long-term predictions of VM resource demand. The objectives of the work were the reduction of the VM performance violations and also the number of hosts in an effort to save energy. CPU usage for both hosts and VMs was forecast, then, the predicted error was computed using a probability density function. Estimating the forecasted values, a fixed threshold decided when hosts would become saturated, and then determined the best place for some of their VMs using the forecast future interval. Although the method is interesting because there is a trade-off between host SLA violations and the penalty of migrating, the procedure is high-time consuming and unfeasible in real scenarios.

Liu et al. in [55] proposed EQVC, a method for preventing host overloading by predicting their utilisation using the ARIMA model. It consolidates VMs to the hosts with the lowest processor utilisation in comparison to other hosts. The results demonstrated the ability of the technique to reduce the energy consumption, guaranteeing QoS and reducing the number of VM migrations.

In terms of the VM to Host allocation process, an optimal power-performance ratio (OPPR) method was proposed by Chehelgerdi et al. in [56]. Its objective was to select the destination hosts of VM during migration. An ARIMA model supported this method, then reported good prediction results when analysing large amounts of host historical data. The drawbacks of the method were the high computational cost and the lack of VM future requirements predictions.

Sharma et al. in [57] proposed an Artificial Neural Network (ANN) based on an independent task scheduler with the aim of reducing energy consumption and then improving the performance. The method only took decisions based on the current state of the Cloud environment. Moreover, the system must be pre-trained, fixing the decisions to the previous knowledge about the set of data.

From the point of view of the Bollinger Bands (BB), traditionally these are combined with Neural Network methods, specially in the stock market field [58, 59], and also in metaheuristics for optimisation problems [60].

Some works can be found, such as Jung et al. [61], which propose an estimated interval-based checkpointing technique (EIC) computed with Bollinger Bands applied to the management of Spot instances. The BB were used to set up the checkpointing based on the average failure probability. In addition, the BB provide users with estimations of time and cost. Badea et al. in [62] proposed a Content Server selection algorithm for VoD systems, using server saturation forecasting based on Bollinger Bands. The proposed system was able to react to changes in traffic volume, redirecting further requests to other servers in the infrastructure.

After observing the behaviour of BB in other research fields, our hypothesis establishes that the use of BB can help to avoid peak situations that produce unnecessary migrations and loss of energy efficiency in the mid- and long-term. By defining confidence margins to be used for predictions of resource usage, it is expected that unnecessary migrations will not be performed, thus minimising the SLA violations and guaranteeing the quality of service.

2.7 Statistical Analysis

Statistical Analysis is the branch of Mathematics that studies the discovery of patterns and tendencies based on existing data. The main goal is to reach reasoned conclusions in order to minimise risky decisions during the scheduling process. The algorithms presented in this thesis are strongly supported by statistical methods in the literature. The following sections complement this chapter with a brief introduction to the techniques utilised in the thesis.

2.7.1 Pearson's Correlation Coefficient

A correlation is the linear relation degree between two set of values over n dimensions. It is expressed with a ratio inside a defined range. Principally, this range is [-1, 1], where 1 indicates a direct relation, 0, no relation, and -1, indirect relation. Intermediate values show the tendency between defined states. Correlation methods are useful for finding patterns between different data, although the existence of correlation does not mean causality, but it can exist.

In the case of hosts and VMs, the correlation between the CPU usage of a set of VMs and its hosts over time is a symptom of causality. The behaviour of a host is completely determined by the demand of its VMs. Then, the VMs directly correlated with the host contribute together to altering the host CPU utilisation.

Pearson's Correlation Coefficient assumes n samples of two variables, x and y. It is calculated by Eq. 2.13, where $\bar{x}$ and $\bar{y}$ represent the arithmetic mean of x and y, respectively. In addition, each pair of values corresponding to the same point in time cannot be altered so as to maintain the consistency of the coefficient obtained.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{2.13}$$

The fact that there is a correlation is not enough to determine the Host's most representative VMs. The addition of a multiplicative weight w helps to tune the correlation value taking into account the percentage of usage of each VM over the whole demand. Further information about Pearson's Correlation Coefficient can be found in Chapter 3 in Section 3.2.

2.7.2 Bollinger Bands

In finances, the Bollinger Band (BB) method is used to discern the volatility of assets, helping to decide how to proceed. These decisions are based on variability, stability and trend changes in its values. Practically, BB is an indicator composed of a Simple Moving Average (SMA), a lower band (LB) below the SMA and an upper band (UB) above the SMA. The LB (Negative Standard Deviation) and the UB (Positive Standard Deviation) are calculated from the standard deviation (σ) according to equations (2.14) and (2.15), respectively. The Moving Average (MA) is a statistical measure that calculates the mean of n near values for each element in a timeseries in the range $[m, o]$, resulting in another timeseries with $o - m - n + 1$ elements.

Figure 2-4 shows an example of BB application with a window of 12, the number of historic data to calculate SMA, and an alpha value (α) of 2.

$$LB = SMA - \alpha \times \sigma \tag{2.14}$$

$$UB = SMA + \alpha \times \sigma \tag{2.15}$$

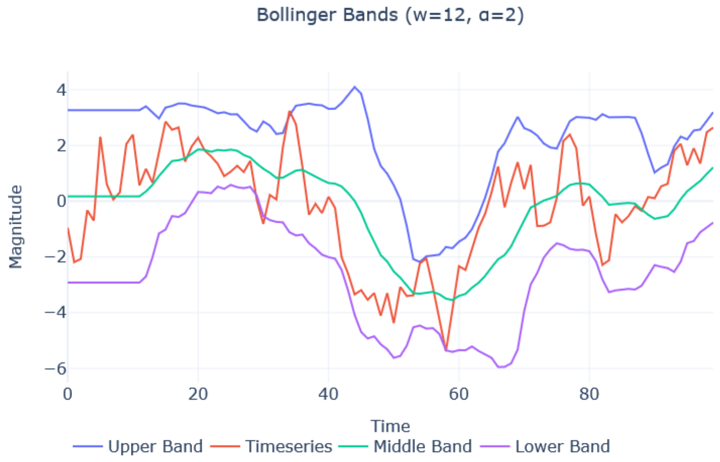

Figure 2-4: Example of Bollinger Bands

2.7.3 Neural Network Forecasting

Neural Network (NN) Forecasting methods have the ability to approximate nonlinear functions by analysing the characteristics of the timeseries information provided. The knowledge already in the NN is used to hide part of these data, recreating it again with the rest. This allows the model to be tuned in each iteration to cover more and more experienced situations, detecting behaviour patterns applicable to non-trained circumstances, and reducing the offset errors against the real data.

The utilisation of NN for forecasting purposes is a game changer in the field of resource demand, usually based on linear regression methods. The existing host saturation detection methods benefit especially from NN, being able to obtain more reliable decisions because not only can they use the past and current resource demand but the future one with more accuracy.

Facebook Prophet

Prophet is a predicting method focused on timeseries data based on additive models that fit non-linear trends. The evaluated seasonal time periods can be classified into annual, weekly and daily, and it is possible to include holiday adjustments. This framework obtains good results in the prediction of timeseries, being able to identify their trend.

Prophet bases its forecasting hypothesis on a classic decomposable time series model [63]:

$$y(t) = g(t) + s(t) + h(t) + \epsilon_t \tag{2.16}$$

where $g(t)$ manages the general trend function, $s(t)$ is the representation of periodic changes, $h(t)$ digests the effects of special and punctual events, ϵ_t, the error term, collects the offsets that do not follow the tendency and corrects them to allow the original data finally to fit. It is assumed that ϵ_t is normally distributed during the forecasting estimations.

Neural Prophet

Recently, various Machine-Learning (ML) based tools for automate time series forecasting have appeared. These tools are distinguished by their ability to automate the process of creating explainable and scalable ML models which scale to many real-world forecasting applications. NeuralProphet [14], the successor to Facebook

Prophet, fuses the classic interpretable time series statistics with scalable Neural Networks (NN) modules into an efficient hybrid model. These NN modules are fitted to non-linear dynamics and performing tasks like auto-regression, next-step forecasting, multi-step forecasting, specific step forecast and long-term forecast horizon, therefore being able to provide a near-term future prediction with less significant cost. In this paper, a Neural Prophet-based technique, referred to as NeoPro, is proposed. It is designed to identify both the future trend in the host load and the VM requirements. The forecasting obtained allows the scheduler to anticipate the resource status and so take more suitable action.

Chapter 3

Papers

> What is not defined cannot be measured. What is not measured, cannot be improved. What is not improved, is always degraded
>
> *William Thomson Kelvin*

During this thesis, various contributions have been made in the form of publications in scientific journals, as well as attendance and presentations at conferences. In the Chapter 4, a mention is made of each of the contributions relating them to the initial hypotheses of the thesis and the defined milestones.

In this chapter, it is presented the papers which are the main core of the current PhD. The schema in Figure 3-1 shows how the different topics dealt with in the thesis were treated and which ones influenced the others.

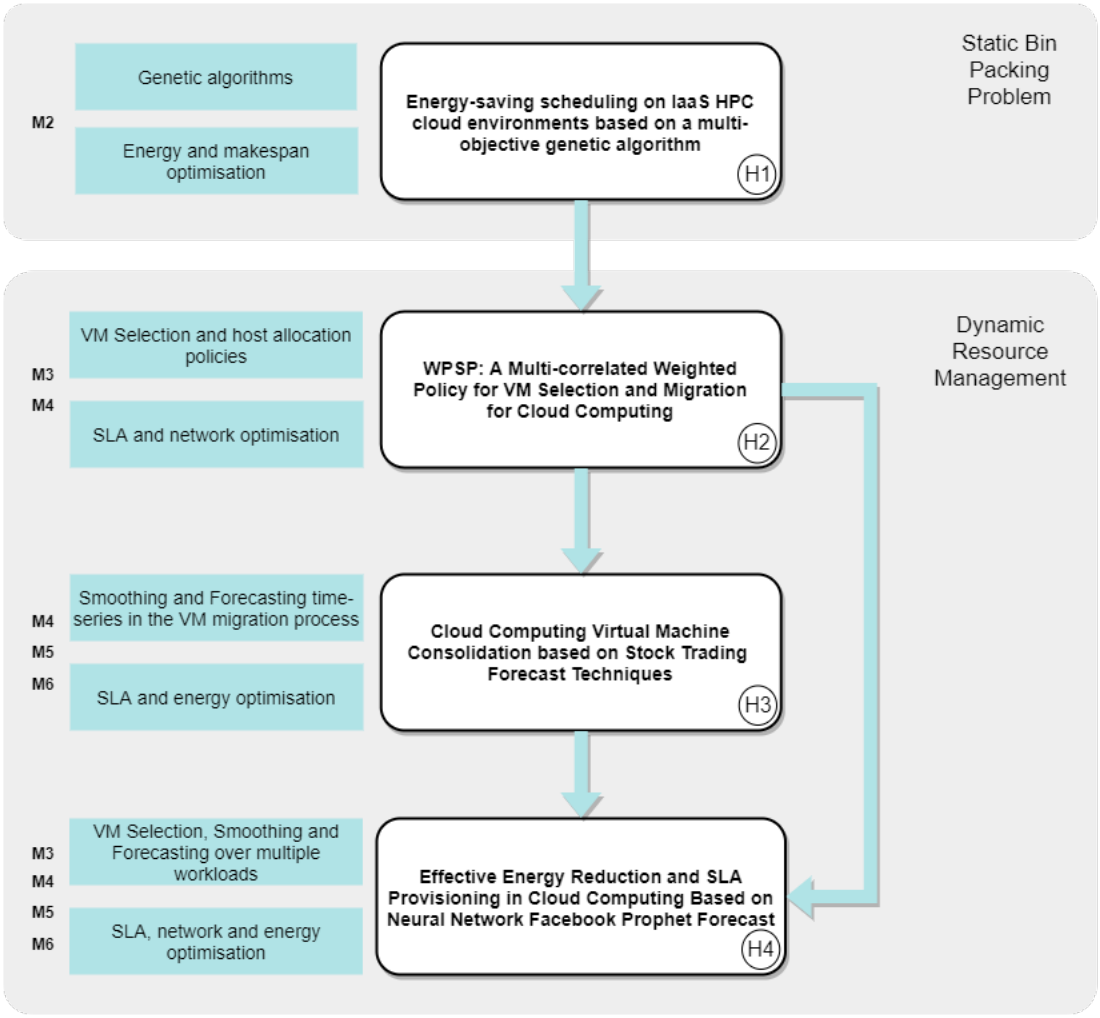

Figure 3-1: Papers workflow

Each of the papers is presented below, emphasising its contribution and main conclusions.

3.1 Energy-saving scheduling on IaaS HPC cloud environments based on a multi-objective genetic algorithm

The paper can be found in the following publication:

Authors	Sergi Vila, Fernando Guirado, Josep L. Lérida, Fernando Cores
Title	Energy-saving scheduling on IaaS HPC cloud environments based on a multi-objective genetic algorithm
Journal	The Journal of Supercomputing
Publication	Volume 75 Issue 3 Pages 1483-1495
Date	March 2019
Impact Index (SCI/SSHI/AHCI)	2.157
Quartile and Subject (SCI/SSHI/AHCI)	Q2, Computer Science Interdisciplinary Applications
Number of citations	16 (Scopus)
ISSN	0920-8542
DOI	https://doi.org/10.1007/s11227-018-2668-z

The Distributed Computing Research Group (Grup de Computació Distribuïda, GCD) at the University of Lleida has extensive experience in the study of Grid, multi-cluster and federated-clusters [64, 65, 66], from the resource scheduling point of view, and recently has started new research lines into applications running on Cloud environments applied to several social and industrial fields, such as agro-industry [67] or medicine [68], both focused on the application optimisation perspective.

The present paper focuses the research line on resource scheduling and analyses the applicability of the group expertise and method developed, but now to Cloud

Computing environments. In previous works, it was demonstrated that the use of genetic algorithms improved the makespan of the parallel applications and the energy consumption of the execution platform in federated environments [31, 69, 70, 71].

Cloud datacenters can be defined as the evolution of the previous computing infrastructures, which are composed of a set of hosts, all prepared to run multiple and heterogeneous VMs, which contain heterogeneous VMs with different number of cores and MIPS capacity. Thus, previous research group methods are taken to be a valid opportunity for the Cloud infrastructure.

From the point of view of the scheduling problem, the paper models the problem as a bin-packing challenge, the main goals being the minimisation of the makespan for a set of cloudlets and also the reduction of the global energy consumption.

The core algorithm to implement the proposed idea is based on the Global Weighting Achievement Scalarizing Function Genetic Algorithm (GWASF-GA), whose main purpose is to approach the Pareto optimal front for multiple objectives. GWASF-GA uses a black-list to decide the priority of each task co-allocation, that is, for each host and task pair, the percentage of cores where the task cannot be allocated.

The black-list matrix defines the chromosomes in the genetic algorithm, then each one offers a restricted core VM access for each cloudlet solution. Thus, it is given the opportunity for further cloudlets in the assignation list to be assigned in the current VMs. In each generation, the population generates offspring after applying the fitness function. The best Pareto front scores are selected, and then, crossover operations are applied to join other individuals.

3.1.1 Contribution

This paper was focused in the research transition from the Federated Computing environments to Cloud Computing. The main idea is to corroborate that the methods and meta-heuristics previously defined can be applied or at least used as the starting point, for the present thesis research, accomplishing with M2.

Having said that, a multi-objective genetic algorithm was designed and tested. It was named BLEMO for Black-List Evolutionary Multi-Objective algorithm. BLEMO is initially designed to schedule a High Performance Computing bulk of tasks on a Cloud Computing environment. To do so, each single parallel task was paired with a cloudlet and then allocated to a Virtual Machine (VM). The scheduling goals were defined to obtain the minimum global makespan while obtaining the lowest energy consumption. BLEMO was designed to treat the complete set of tasks as a bin-packing problem.

3.1.2 Results

To validate the results, various HPC real workload traces were used, namely HPC2N, CEA-Curie and SANDIA. All of these were tested by simulation, based on the CloudSim tool, defining an Amazon EC2 Cloud environment with 200 available cloudlets.

BLEMO obtained the following improvements for each workload analysed:

- For the CEA-Curie workload, BLEMO reduced the makespan by up to 42.40% and the energy consumption by 40.15%.
- With the HPC2N workload, the improvements were reductions of 53.35% for the makespan and 46% for energy consumption.
- Finally, the Sandia workload obtained the highest improvements over the heuristic algorithms, of around 60% in makespan and 50% in the energy consumption.

The results confirmed that the usage of Evolutionary algorithms improves the multi-objective purpose of reducing the makespan and energy consumption, obtaining a minimum global 40% improvement in both metrics and 2-4 times less dispersion than the compared techniques.

3.2 WPSP: a multi-correlated weighted policy for VM selection and migration for Cloud Computing

The paper can be found in the following publication:

Authors	Sergi Vila, Josep L. Lérida, Fernando Cores, Fernando Guirado, Fabio L. Verdi
Title	WPSP: a multi-correlated weighted policy for VM selection and migration for Cloud computing
Conference	Euro-Par 2020: Parallel Processing (European Conference on Parallel Processing)
Journal	Lecture Notes in Computer Science
Publication	Pages 312-326
Date	August 2020
Impact Index (SJR)	0.249
Quartile and Subject (SJR)	Q3, Computer Science
Number of citations	–
ISSN	0302-9743
DOI	https://doi.org/10.1007/978-3-030-57675-2_20

In Cloud Computing platforms, multiple virtual machines sharing computing resources coexist in the same host. Because VMs have a completely heterogeneous workload, their requirements are totally different. In addition, the behaviour of these workloads usually has peaks and uncontrolled variations meaning that the host may not be capable of covering the full load demanded by the VMs, thus causing user SLA violation.

VM migration is an affordable method for regulating the CPU load of datacenters without sacrificing computation power as other methods like DVFS do [72, 73]. Through migration, the VMs can be relocated to other hosts with enough computational resources to support the VMs' needs.

Thus, the VM migration process starts upon detecting a host saturation state. It is at this moment when it is necessary to decide the most suitable VM to be reassigned to a new host. The choice of the VM is not trivial, since not only it is necessary to ensure that the VMs to be reassigned obtain the necessary resources in the destination host, but also that enough computational resources are freed in the current host so that the VMs that remain can continue to run without any issues.

In the present paper, WPSP (Weighted Pearson Selection Policy), has been proposed. This has been obtained as a result of the close collaboration with the LERIS (Laboratory of Network, Innovation and Software Studies), Departamento de Computação, UFSCar Campus Sorocaba.

WPSP applies Pearson's Correlation to enable the VMs that have CPU and network host correlation usage to be highlighted [74]. It also takes into consideration the relative weight of the VM demand in the correlation calculus, and then obtains the VMs most influencing their host. This weight, defined as the h-index, identifies the VMs with highest CPU influence and lowest impact on communications.

Moreover, the paper also includes a policy that complements WPSP in the migration process, the Minimum Distance Group (MDG) algorithm. The MDG focuses on reducing the distances between hosts with communicating VMs, when a VM is migrated. The candidate hosts are tested in group by hop distance from near to far. When a group contains one or more hosts that can allocate the incoming VM, the one that produces a lower increment in energy consumption is selected.

3.2.1 Contribution

This paper was completely based on the Cloud Computing environment, making a step forward in the progress of the thesis. The main contribution of the paper is the Weighted Pearson Selection Policy (WPSP) that is able to identify the VMs that affect the host status significantly, in both metrics, namely CPU and network usage.

The main goal of WPSP is the reduction of the number of migrations, trying to do just those that are really necessary and then ensuring VM consolidation and thus, fewer SLA violations and lower energy consumption.

Milestone M4 is dealt with in the present paper with the development of WPSP, improving the VM Selection step. Moreover, the metrics analysed by WPSP and during the experimentation are related with milestone M3.

3.2.2 Results

WPSP is compared with the other classic algorithms in the literature focused on VM selection. These are Maximum Correlation, Minimum Migration time, Minimum Utilization and Random Search.

The Cloud topology used in the experimental study was based on a tree structure with 36 heterogeneous hosts that allocate 400 VMs. VMs were defined with 4 different resource configurations. The VMs executed PlanetLab traces [75] and sin-cyclostationary bandwidth interactions among several VMs were defined to take into consideration the VM network usage.

As a result of the WPSP proposal, the number of migrations was reduced by up to 89% in relation with the other techniques tested. This had a direct impact on the reduction of up to 87% in the number of MBs moved through the network due to VM communications. Moreover, the bandwidth used was reduced by up to 5% and the network saturation by up to 20%.

The results show that the use of the MDG algorithm produces a reduction of up to 90% in the quantity of data moved due to VM migrations. Furthermore, the combination of WPSP and MDG obtained reductions of 51% in the number of unsatisfied hosts (those that cannot execute the assigned load), 5% in bandwidth used and required up to 90% fewer migrations.

Both techniques, WPSP and MDG, achieved their objective of making the datacenter much more efficient, decreasing the resources consumed in terms of MIPS execution, number of VMs migrated and the bandwidth used.

3.3 Cloud Computing Virtual Machine Consolidation based on Stock Trading Forecast Techniques

The following paper has been delivered to the Future Generation Computer Systems Journal and is currently under review.

Authors	Sergi Vila, Fernando Guirado, Josep L. Lérida
Title	Cloud Computing Virtual Machine Consolidation based on Stock Trading Forecast Techniques
Journal	Future Generation Computer Systems
Impact Index (SCI/SSHI/AHCI)	7.187
Quartile and Subject (SCI/SSHI/AHCI)	Computer Networks and Communications (Q1); Hardware and Architecture (Q1); Software (Q1)
ISSN	0167-739X

One of the most relevant highlights during the present PhD work is that the number of migrations has a considerable impact on several aspects of Cloud Computing environments, the most relevant being the energy consumption and the SLA degradation suffered by the VM load when the migration is done without any restriction.

Bearing in mind the reduction in the number of migrations, and the need to ensure only the essential ones are done, a research line was initiated to find new approaches and solutions to the migration process.

It has been demonstrated in the literature that the migration process can provide great benefits but should be applied cautiously. This is because after deciding to migrate a VM, it should be ensured that the resources in the target host will be available long enough to ensure efficient execution of the VM, otherwise new migrations will occur.

To identify and execute those migrations that are completely necessary effectively, the present paper explores a different approach to the problem. The idea is that at the time of determining the candidate VM to be migrated, not only is it necessary to determine the current VM resource requirements but also the future ones. With this knowledge it could be possible to identify accurately which host is the most suitable to allocate the VM to.

This requires having the ability to predict the VM resource requirements, which is no easy topic. Furthermore, to have a successful solution the forecast process should be done at the host level to determine the availability of its resources.

This paper proposes a method focused on predicting the behaviour of VMs and hosts and its effectiveness is evaluated from the point of view of the number of migrations and the reduction in energy consumption.

The main goal focuses on determining the efficiency of the proposal as well as defining the steps in the scheduling process that should be applied to obtain maximum performance.

The forecast process is not easy and there are multiple methods in the literature. These include an initial and in-depth study that tested multiple methods and finally selected the NeuralProphet, which is one of the most recent ML forecasting methods. A second component was implemented, the Bollinger Bands, which allows the chaotic workload traces to be smoothed, catching the most relevant features and avoiding the unexpected computational peak loads that provide false requirement expectations.

Thus, the proposal, named BB+NeoPro for the Bollinger Bands and the Neural Prophet components, was designed and focused on optimising energy consumption with the minimal SLA repercussion.

3.3.1 Contribution

To evaluate energy consumption effectively, an enhanced energy model is adopted that takes into account the consumption of the running hosts, the energy spent during VM migrations and the startup and power-off of physical hosts.

The migration process was implemented in the CloudSim simulator scheduling process stack including all the components of the proposal, the Bollinger Bands and the Neural Prophet (NeoPro) framework.

Finally, the most important contribution refers to two aspects. The first one corresponds to the verification that the prediction process, in the use of resources by the VMs as well as in their availability in the hosts, produces great benefits in reducing the number of migrations and energy consumption.

The second contribution is the definition of the steps that must be followed in the scheduling process in order to obtain the benefits of the prediction process.

A further step is taken in the milestone M4 using BB+NeoPro, which affects the whole VM migration process except for the VM selection step. The goal of milestone M6 based on the use of forecasting methods for scheduling optimisation, fits perfectly with the algorithms developed in the work, which additionally accomplishes milestone M5 due to great improvements in the energy consumption.

3.3.2 Results

The main objective of this paper is to validate that the forecast process can be a useful tool for consolidating VM allocation, which will reduce the number of migrations and the hosts used, and then finally have great benefits through the reduction of energy consumption.

The proposal was extensively analysed by simulation on the CloudSim platform. Initially, the effectiveness of the VM allocation obtained was determined when BB+ NeoPro was used in conjunction with different techniques from the literature used to identify the host saturation status. The influence of the obtained prediction on the several allocation techniques was also evaluated. The results of the analysis demonstrated great benefits after applying BB+NeoPro to those traditional techniques.

The reduction of the number of migrations, which was up to 15% compared with the classic techniques when there was no help from a forecast. This had positive benefits for datacenters, including a reduction of up to 60-75%, in VM migrations, around 4-16% for energy consumption and a drop in SLA Violation of 40-60%.

The robustness of BB+NeoPro was also analysed for different infrastructure configurations and several workloads from PlanetLab. In all cases the results were fewer SLA violations, a minimal number of migrations and a reduced energetic cost.

Finally, the initial hypothesis which proposed that the forecast process applied to the VMs migration process would be really useful, had been successfully corroborated.

3.4 Effective Energy Reduction and SLA Provisioning in Cloud Computing Based on Neural Network Facebook Prophet Forecast

The following paper has been delivered to the IEEE Trans. on Cloud Computing Journal and is currently under review.

Authors	Sergi Vila, Fernando Guirado, Josep L. Lérida
Title	Effective Energy Reduction and SLA Provisioning in Cloud Computing Based on Neural Network Facebook Prophet Forecast
Journal	IEEE Trans. on Cloud Computing
Publication	Under review
Impact Index (SCI/SSHI/AHCI)	5.59
Quartile and Subject (SCI/SSHI/AHCI)	Computer Networks and Communications (Q1); Computer Science Applications (Q1); Computer Science (miscellaneous) (Q1); Software (Q1)
ISSN	2325-6095

After validating the performance of the smoothing and forecasting techniques proposed in the previous paper, the last contribution to this PhD thesis is based on the combination of these techniques with the knowledge learned in the second contribution, which was focused on the correlation of VM and host CPU and network usage to identify the VMs that should be migrated.

In the second main paper, it was demonstrated that the WPSP technique had a great impact on the VM candidate selection to be migrated. The technique was able to select the VMs highly correlated with the CPU host and low communications.

In the present paper, the combination of WPSP with the forecasting methodology is proposed in order to provide much more consistent results in the migration process.

The Bollinger-Bands were maintained as the smoothing technique as it was previously demonstrated that they effectively avoid unexpected VM and host peaks loads. The FacebookProphet framework was chosen for the forecast proposal. This is successfully applied in a wide range of fields that require the forecast process, such as industrial and domestic energy consumption [76], COVID-19 evolution [77], or hydro-power generation [78] for example.

The proposal in this paper, named WBF (for WPSP + Bollinger Band + FacebookProphet), has been widely analysed. Thus, with the purpose of determining the applicability of the proposal on any different scenario, the present paper analysed several workloads from different cloud providers, namely PlanetLab, Alibaba, Materna and Azure.

3.4.1 Contribution

Because the energy consumption is an important metric that it is affected at multiple layers in the infrastructure, the energy consumption model was refined and updated in order to take into account the different actions that are involved during the migration process and also the complete set of hardware that is part of the network infrastructure. Thus, the full fine-grained energy model is aware of:

- Host CPU load
- Host power-on and power-off drawbacks
- Inter-communications at host and switch level
- VM migrations at host and switch level

The proposal was implemented in the scheduling process of the Cloudsim simulator and compared with different VM migration selection techniques. In order to ensure full knowledge of how each component in the proposal acts and what it contributes to the experimental results, the study also analysed each one separately. Thus, WPSP, WF and WBF were added to the comparison.

The WBF proposal covers most of the milestones identified in Chapter 1. It required a complete study of the literature to understand the forecasting process (M0), and also hard work to redefine the experimental tools to allow its integration into the CloudSim simulator (M1). It is based on the WPSP method that identifies the most relevant features of the VMs to be migrated (M3). Furthermore, its main goals are the optimisation of the migration process and the reduction in energy consumption (M4 & M5). Finally, it is based on the forecasting process to achieve its goals (M6). Having said that, the WBF can be considered as one of the most relevant aspects of this PhD.

3.4.2 Results

The experimental study evaluated several methods from the literature and compared the results with the standalone WPSP execution and the WBF proposal. The use of the method disabling the Bollinger Bands (WF), also taken into consideration, just to determine the effect of the smoothing process.

Four different workloads were tested: PlanetLab, Alibaba, Materna and Azure; each of them from different Cloud providers and exhibiting different behaviours.

The results show that the use of only WPSP led to a remarkable reduction in the number of migrations of at least 40% independently of the workload. WF and WBF were able to reduce this previous mark with improvements of 30% and 40% respectively in comparison with WPSP. From the point of view of energy consumption, WPSP obtained excellent results (up to 10-13%) compared with the classic methods in all the workloads.

Specifically for the PlanetLab and Materna workloads, WF was able to reduce the energy consumption (12-19%) and also obtain a lower SLA Violation (11-16%) than classic methods. Moreover, CPU efficiency was improved by 21-33%. Regarding WBF, the results were even better, sacrificing part of the energy consumption optimisation for Materna (6.7%) to obtain a 38% reduction in SLA Violation.

Due to the low variability of Alibaba, WPSP and WF decides to not move VMs due to the demand being on the limit of host saturation, although this limit is sometimes crossed, generating short saturation. For this reason, there are difficulties to maintain a low SLA violation. Despite this, energy consumption is reduced by 13% and 8% for WF and WFB, respectively. Furthermore, the MIPS/Energy ratio (ME in the paper) showed that the three methods are more CPU optimal over energy than MRM by 8.44% (WPSP), 10% (WF) and 7.34% (WBF).

Finalising with Azure, the results are similar to Planetlab and Materna with the difference that only WBF is able to obtain benefits over SLA Violation (6.5%) in relation to MRM. Even though, the ratio ME is still optimised on 8.9% (WSP), 10.75% (WF) and 6.33% (WBF).

An important result refers to the way in which the proposal acts depending on the nature of the workload. For those workloads with unstable behaviour and large variations (PlanetLab and Azure), WBF is capable of offering very good results, by being able to identify when the VMs or the hosts will or will not remain stable and then promoting the migrations effectively. On the contrary, for stable workloads (Alibaba and Materna), the forecast process avoids doing migrations that were identified as unnecessary. This causes a slight degradation of VM MIPS execution degradation but with great energy benefits.

Finally, it can be concluded that the proposed technique allowed datacenter administrators to reduce energy consumption by 10%, improved SLA by up to 25-60% (except for Alibaba), and reduced the number of migrations by 45-70%, leading to a 40-60% improvement in communications due to migrations.

Chapter 4

General Conclusions and Future Work

> When you reach the end of what
> you should know, you will be at the
> beginning of what you should sense
>
> *Khalil Gibran*

4.1 Conclusions

In Cloud Computing, resources from the datacenter are delivered to users according to their needs as a service in many different ways, IaaS, PaaS and SaaS being the most common among these. Datacenter resource management becomes a challenging problem when trying to optimise the user-service requirements under the platform constraints.

In the research work presented previously, an innovative way of dealing with scheduling in Cloud Computing platforms was presented. In an initial phase, an approach based on meta-heuristics and accumulated knowledge in the GCD research group was carried out. For this, a Multi-Objective Genetic Algorithm, named BLEMO, was developed. This was mainly focused on reducing both the makespan and energy consumption. The proposal was implemented using the GWASF-GA optimisation.

BLEMO incorporates the Black-List concept that determines the unavailable cores in the VMs for each cloudlet instead of the available ones.

This approach was able to generate scheduling decisions evading systematic allocations and providing new chances for the remaining cloudlets to be scheduled in order to reduce the overall execution time and also the energy consumption. Our proposal was validated using real workload traces from HPC environments and comparing the results with well-known algorithms from the literature. The results obtained show that our proposal achieved lower execution times and energy consumption compared with other classic algorithms from the literature.

This initial step done in the PhD research gave the opportunity to know more precisely one of the biggest problems in Cloud Computing environments. The variable nature of the virtual machines (VM) behaviour means that, on a large number of occasions, the hosts on the platform become saturated in an uncontrolled manner. This situation forces the scheduler to readjust the workload assigned to the hosts continually. This is mainly carried out through the migration process. In this process, some of the VMs assigned to the saturated host are moved to another host with enough available resources.

The choice of the VM to migrate is not trivial since there are many variables to keep in mind, including not only the computational resources necessary to ensure the smooth execution of the VMs, but also the efficient management of the resources in the hosts, and therefore the reduction of energy consumption.

For this reason, the next step in the development of this thesis focused on solving the problem of identifying precisely which VMs are really affecting host saturation. In this process, both the consumption of computational resources, CPU, and the use of the communication network were taken into account.

Thus, a VM selection policy, named WPSP for “Weighted Pearson Selection Policy”, based on the Pearson Correlation Coefficient, was defined. The weighting values that allow the influence of the VM CPU and Network utilisation on the Host to be evaluated were also defined. The results obtained demonstrated that WPSP reduced the Hosts overload by up to 10% compared with other methods from the literature and also gave a significant reduction of up to 20% in the network data traffic. Furthermore, WPSP was able to reduce the number of migrations by up to 89%, which provided better resource usage and load balance.

One of the most important contributions of the results obtained in the previous work was the fact that migrations are one of the most influential factors in the behaviour of the Cloud platform.

After an exhaustive analysis of the VM migration process, the author came to the conclusion that it is not only necessary to take into account the current state of the need for resources by the VMs and the availability of hosts. The behaviour, requirements and future availability of both actors should be identified to ensure an efficient migration, which also allows an effective stability and consolidation of the VM/host pair. Thus the main core of the proposal is to develop the methods and provide the required ability to predict the behaviour of both VMs and hosts.

Thus, the research was directed towards the definition of a model of integration for the prediction process in the different steps carried out during scheduling. Likewise, the objective was to corroborate that the prediction capacity can contribute benefits to the methods for selecting the VMs to migrate as well as to the methods of assigning them to existing hosts.

To achieve the previously defined objectives, it was decided to explore the use of time series forecasting techniques broadly used on stock trading. Thus, the proposal combined the use of Bollinger Bands with the Neural Prophet framework to estimate future resource utilisation based on the historical data of the VMs and hosts. The results obtained with this approach, named BB+NeoPro, demonstrated that the number of VM migrations was greatly diminished, by around 60-75%, reducing SLA violations by 40-60%, and, even more importantly, the reduction of energy consumption of around 4-16%.

The good results obtained by the developed methodology were finally corroborated in the last phase of this thesis. In this final step, the effectiveness of the prediction process was verified using four workloads obtained from different Cloud providers; PlanetLab, Materna, Alibaba and Azure. To do this, Facebook Prophet was chosen as the forecast method, the Bollinger Bands were maintained as a filtering technique and, finally, the previously developed WPSP method was adopted to identify clearly the most relevant VMs to be migrated. These three methods working together enabled the energy consumption to be reduced by 10%, SLA to be improved by between 25-60%, and the number of migrations reduced by 45-70%, in comparison with classic methods in the literature.

All of the aforementioned techniques were tested by simulation mainly using the CloudSim simulator, and hard work was required to implement all of them in it. Furthermore, a sophisticated method to calculate the energy consumption was defined and implemented. This allowed a deep analysis of the energy consumption. Different levels in the Cloud environment, from the host consumption to the network routing, were taken into account in the calculation.

From the initial thesis steps, the simulation platform has been CloudSim. However, due to the incorporation of the thesis proposals, methods, and models, it can be said that the original simulator has been redone being the result a completely different one. Keeping this in mind, it can be said that the present thesis has also concluded in a new Cloud simulator. This has been named as MetaCloudSim. The source code of MetaCloudSim is available to the scientific community on the following link:

MetaCloudSim repository

https://bitbucket.org/svila_phd/metacloudsim/src/vmAllocation/

4.2 Future Work

The main characteristic of Cloud computing platforms is their enormous capacity to adapt to the computing needs of their users. Users, in turn, can be very diverse, posing different needs at the level of computational resources or performance criteria. This makes it very difficult to offer a single solution to satisfy everyone. In addition, from the point of view of the system administrator, the needs of use, performance and energy cost are crucial for a Cloud platform to make sense.

Trying to solve the hypotheses raised in the first chapter meant that, during the development of the present thesis, new elements appeared and generated new possible alternative lines of research to those carried out. All of these remain open for the continuation of the present work. Some are listed below.

- **Resources Requirements**

  In the present work, the computing capacity, in the form of MIPS, was taken into account as the main resource demanded for the execution of the VMs. This parameter was also used to define whether the host is saturated or not to finally start the migration process.

  We consider that there are also other important components that should be analysed:

  - RAM Memory: VMs require an amount of RAM memory to be able to run. This factor should be taken into account in the identification of the hosts that should receive the migrated VMs.
  - Secondary Memory: The use of secondary memory, in the swapping process, should be taken into account as one of the requirements that can identify the saturation of a host.
  - Network Routing: In the fourth article, the energy consumption that occurs during the migration process when crossing different nodes of the network was evaluated. It is considered that one aspect that should be taken into account when identifying the destination hosts of the migrated VMs is the path and distance that must be followed to reach the destination host.

- **Data Locality**

  VMs generally process data that can be found locally or distributed in a different location from the host on which they are running. For this reason, the following elements to be kept in mind are proposed.

  - Local Access: In their requirements for the target host, those VMs that have continuous data access should include the possibility of a capacity factor for access to storage systems, such as speed or latency.
  - Remote Access: Cloud environments are currently widely used for Big-Data processing. Due to the large volume of data that these applications process, it is considered that during the migration process, the approach of the VMs to the data origin or defining a maximum distance from them should be taken into account.

- **Virtual Machine and Containers**

  Containers are currently becoming a standard for deploying applications. Taking advantage of the shared kernel between host and virtualised OS, the interoperability management of resources increases the efficiency and avoids duplicity. In the end, this is reflected in a reduction of the SLA. Although the solutions proposed in this work are focused on VMs, they are compatible with containers in the upper layer. Thus, author proposes adapting the current research to the container model.

- **Cloud Workloads: Analysis and Characterisation**

  The work carried out was based on the simulation of the execution of workloads. In the literature there is little information that characterises specific workloads from Cloud environments. The author carried out an extensive study of multiple workloads, as reflected in the fourth article in Chapter 3, but there are other workloads, such as Bitbrains [79] and Google [80], that could not be used due to lack of time. The author has the intention to carry out a comparative study of the different workloads as well as to continue the validation process of his proposals using these new ones.

4.3 PhD Contributions

Taking the milestones presented in Chapter 1 as a reference, below is the list of papers published. The contributions included in Chapter 3 are highlighted in bold. Moreover, Figure 4-1 links the milestones and hypotheses with the publications:

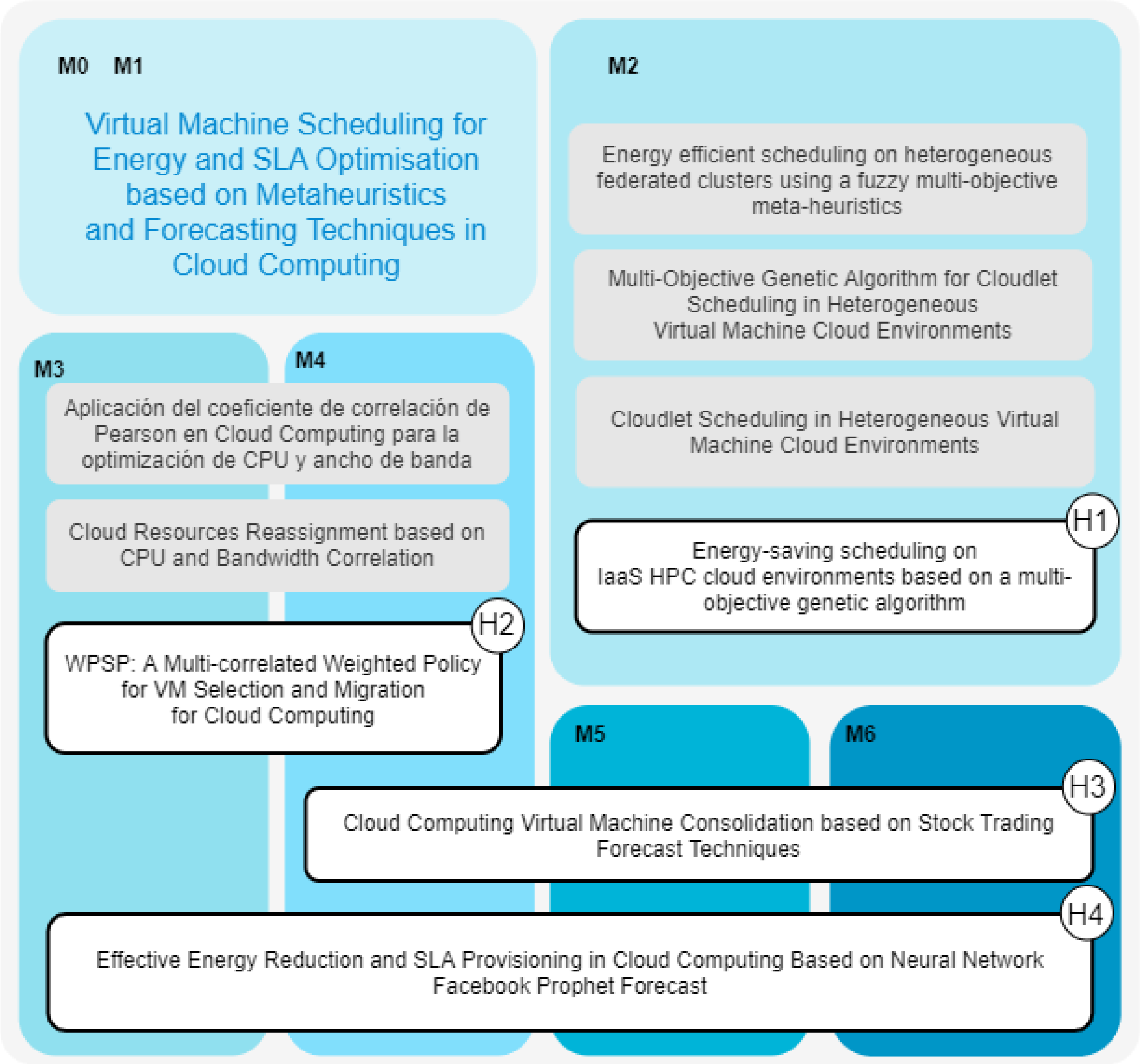

Figure 4-1: Hypotheses, milestones and publications overview

I. Energy efficient scheduling on heterogeneous federated clusters using a fuzzy multi-objective meta-heuristics [71] (FUZZ-IEEE, 2017): The spark that ignites this research. This was the first approach to the development of a scientific paper, assisting Eloi Gabaldon on the conclusion of his PhD. The experience acquired about grid environments and genetic algorithms allowed the development of the following work.

II. Cloudlet Scheduling in Heterogeneous Virtual Machine Cloud Environments [81] (Jornadas de Paralelismo, 2018): The GACLS algorithm is presented as the first iteration of BLEMO in [45].

III. Multi-Objective Genetic Algorithm for Cloudlet Scheduling in Heterogeneous Virtual Machine Cloud Environments [82] (CMMSE, 2018): The next step towards developing a more extensive experimentation using BLEMO.

IV. **Energy-saving scheduling on IaaS HPC cloud environments based on a multi-objective genetic algorithm [45] (Journal of Supercomputing, 2019)**: The first main work of this PhD thesis, presenting the definitive version of BLEMO and an extended experimentation.

V. Aplicación del coeficiente de correlación de Pearson en Cloud Computing para la optimización de CPU y ancho de banda [46] (Jornadas de Paralelismo, 2019): The first iteration in a dynamic cloud environment optimising the VM selection technique.

VI. Cloud Resources Reassignment based on CPU and Bandwidth Correlation [83] (AINA, 2020): That work is the precursor of the WPSP paper, presenting the PSP heuristic, the proof of concept for the final implementation and study.

VII. **WPSP: A Multi-correlated Weighted Policy for VM Selection and Migration for Cloud Computing [47] (EuroPar, 2020)**: The second main work of this thesis where most of the ideas developed in the previous works are expressed, showing the full potential of WPSP.

VIII. **Cloud Computing Virtual Machine Consolidation based on Stock Trading Forecast Techniques (Future Generation Computer Systems, 2022, under review)**: This third main work explores the modification of resource usage time-series to help the algorithms involved in the VM migration process to take better decisions.

IX. **Effective Energy Reduction and SLA Provisioning in Cloud Computing Based on Neural Network Facebook Prophet Forecast (IEEE Cloud Computing, 2022, under review)**: The condensation of all the efforts to optimise datacenters by applying techniques to the whole VM migration process makes up the fourth and final main work.

4.4 International doctoral stay

Between September and December 2018, an international stay was done at UFSCar (Universidade Federal de São Carlos) – Campus Sorocaba, in the city of Sorocaba, Estado de São Paulo, Brazil, under the supervision of Dr. Fábio Luciano Verdi. His research group studies Network and Cloud Computing protocols [84], especially focused on Cloud-Network Slicing [85], the paradigm that allows the virtualisation of networks over physical ones [86].

The collaboration of the LERIS (Laboratory of Network, Innovation and Software Studies) and the GCD (Grup de Computació Distribuïda) consisted of the implementation of the Final Master Thesis work from Nilson Moraes. The work, "Improving Load Balancing in Virtualized Environments using Pearson's Correlation" [74], consists of the implementation of a heuristic to select appropriate VMs to migrate due to saturation issues, taking into account the ratio between CPU and network usage.

The tasks developed were:

- Understanding the problem to solve
- Modelling the problem
- Proposing the hypothesis
- Generating synthetic network workloads
- Implementing correlation functions, including Pearson's Correlation

- Implementing the network module for CloudSim, including statistics and plots
- Carrying out experiments to validate the hypothesis
- Starting the research paper with the results obtained

Bibliography

[1] Xiaobo Fan, Wolf-Dietrich Weber, and Luiz Andre Barroso. Power provisioning for a warehouse-sized computer. *ACM SIGARCH computer architecture news*, 35(2):13–23, 2007.

[2] Dara Kusic, Jeffrey O Kephart, James E Hanson, Nagarajan Kandasamy, and Guofei Jiang. Power and performance management of virtualized computing environments via lookahead control. *Cluster computing*, 12(1):1–15, 2009.

[3] Eric Masanet, Arman Shehabi, Nuoa Lei, Sarah Smith, and Jonathan Koomey. Recalibrating global data center energy-use estimates. *Science*, 367(6481):984–986, 2020.

[4] Bertoldi P, Avgerinou M, and Castellazzi L. Trends in data centre energy consumption under the european code of conduct for data centre energy efficiency. *JRC Publications Repository*, 1(KJ-NA-28874-EN-N), 2017.

[5] Nathan Bennett and G James Lemoine. What a difference a word makes: Understanding threats to performance in a vuca world. *Business Horizons*, 57(3):311–317, 2014.

[6] SP Anbuudayasankar, Ramesh Srikanthan, Margabandu Karthik, Prashant R Nair, Nagarajan Sivakarthik, and Packirisamy Indukumar. Cloud-based technology for small and medium scale enterprises: a decision-making paradigm using ipa, ahp and fuzzy-ahp techniques. *International Journal of Integrated Supply Management*, 13(4):335–352, 2020.

[7] Bhagyashree Mohanta, Pragyan Nanda, and Srikanta Patnaik. Management of vuca (volatility, uncertainty, complexity and ambiguity) using machine learning techniques in industry 4.0 paradigm. In *New Paradigm of Industry 4.0*, pages 1–24. Springer, 2020.

[8] W. Richards Adrion. Research methodology in software engineering. *ACM SIGSOFT Software Engineering Notes, Summary of the Dagstuhl Workshop on Future Directions in Software Engineering*, 18(1):36–37, 1993.

[9] Mohit Kumar, S.C. Sharma, Anubhav Goel, and S.P. Singh. A comprehensive survey for scheduling techniques in cloud computing. *Journal of Network and Computer Applications*, 143:1–33, 2019.

[10] AR. Arunarani, D. Manjula, and Vijayan Sugumaran. Task scheduling techniques in cloud computing: A literature survey. *Future Generation Computer Systems*, 91:407–415, 2019.

[11] Raja Wasim Ahmad, Abdullah Gani, Siti Hafizah Ab. Hamid, Muhammad Shiraz, Abdullah Yousafzai, and Feng Xia. A survey on virtual machine migration and server consolidation frameworks for cloud data centers. *Journal of Network and Computer Applications*, 52:11–25, 2015.

[12] Manoel C. Silva Filho, Claudio C. Monteiro, Pedro R.M. Inácio, and Mário M. Freire. Approaches for optimizing virtual machine placement and migration in cloud environments: A survey. *Journal of Parallel and Distributed Computing*, 111:222–250, 2018.

[13] Edsger W Dijkstra. A note on two problems in connexion with graphs. *Numerische mathematik*, 1(1):269–271, 1959.

[14] Imad Sarji, Cesar Ghali, Ali Chehab, and Ayman Kayssi. CloudESE: Energy efficiency model for cloud computing environments. *2011 International Conference on Energy Aware Computing, ICEAC 2011*, 2011.

[15] Edouard Outin, Jean-Emile Dartois, Olivier Barais, and Jean-Louis Pazat. Seeking for the optimal energy modelisation accuracy to allow efficient datacenter optimizations. In *2016 16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid)*, pages 535–539. IEEE, 2016.

[16] Dror G. Feitelson. Parallel workloads archive. `https://www.cs.huji.ac.il/labs/parallel/workload/index.html`, 2005. [Online; accessed June-2022].

[17] Dror G Feitelson, Dan Tsafrir, and David Krakov. Experience with using the parallel workloads archive. *Journal of Parallel and Distributed Computing*, 74(10):2967–2982, 2014.

[18] Princeton University. Planetlab. `https://planetlab.cs.princeton.edu/`, 2019. [Online; accessed June-2022].

[19] Alibaba. Alibaba cloud. `https://eu.alibabacloud.com/`, 2022. [Online; accessed June-2022].

[20] Alibaba. Alibaba cluster trace program. `https://github.com/alibaba/clusterdata`, 2022. [Online; accessed June-2022].

[21] Yue Cheng, Zheng Chai, and Ali Anwar. Characterizing co-located datacenter workloads: An alibaba case study. In *Proceedings of the 9th Asia-Pacific Workshop on Systems*, pages 1–3, 2018.

[22] Jing Guo, Zihao Chang, Sa Wang, Haiyang Ding, Yihui Feng, Liang Mao, and Yungang Bao. Who limits the resource efficiency of my datacenter: An analysis of alibaba datacenter traces. In *2019 IEEE/ACM 27th International Symposium on Quality of Service (IWQoS)*, pages 1–10. IEEE, 2019.

[23] Qizhen Weng, Wencong Xiao, Yinghao Yu, Wei Wang, Cheng Wang, Jian He, Yong Li, Liping Zhang, Wei Lin, and Yu Ding. MLaaS in the wild: Workload analysis and scheduling in Large-Scale heterogeneous GPU clusters. In *19th USENIX Symposium on Networked Systems Design and Implementation (NSDI 22)*, pages 945–960, 2022.

[24] Shutian Luo, Huanle Xu, Chengzhi Lu, Kejiang Ye, Guoyao Xu, Liping Zhang, Yu Ding, Jian He, and Chengzhong Xu. Characterizing microservice dependency and performance: Alibaba trace analysis. In *Proceedings of the ACM Symposium on Cloud Computing*, pages 412–426, 2021.

[25] Materna. Materna about page. `https://www.materna.com/EN/About-us/about-us_node.html`, 2022. [Online; accessed June-2022].

[26] Andreas Kohne. Materna traces. `http://gwa.ewi.tudelft.nl/datasets/gwa-t-13-materna`, 2022. [Online; accessed June-2022].

[27] Andreas Kohne, Marc Spohr, Lars Nagel, and Olaf Spinczyk. Federatedcloudsim: a sla-aware federated cloud simulation framework. In *Proceedings of the 2nd International Workshop on CrossCloud Systems*, pages 1–5, 2014.

[28] Microsoft. Azure. `https://azure.microsoft.com/`, 2022. [Online; accessed June-2022].

[29] Microsoft. Azure public dataset. `https://github.com/Azure/AzurePublicDataset`, 2021. [Online; accessed June-2022].

[30] Concepcio Roig, Ana Ripoll, and Fernando Guirado. A new task graph model for mapping message passing applications. *IEEE Transactions on Parallel and Distributed Systems*, 18(12):1740–1753, 2007.

[31] Eloi Gabaldon, Josep L. Lerida, Fernando Guirado, and Planes Jordi. Blacklist muti-objective genetic algorithm for energy saving in heterogeneous environments. *Journal of Supercomputing*, 73(1):354—369, 2017.

[32] Hector Blanco, Josep L. Lérida, Fernando Cores, and Fernando Guirado. Multiple job co-allocation strategy for heterogeneous multi-cluster systems based on linear programming. *The Journal of Supercomputing*, 58:394–402, 2011.

[33] S Binitha, S Siva Sathya, et al. A survey of bio inspired optimization algorithms. *International journal of soft computing and engineering*, 2(2):137–151, 2012.

[34] Zoltán Adám Mann and Máté Szabó. Which is the best algorithm for virtual machine placement optimization? *Concurrency and Computation: Practice and Experience*, 29(10):e4083, 2017.

[35] Dr Agarwal, Saloni Jain, et al. Efficient optimal algorithm of task scheduling in cloud computing environment. *arXiv preprint arXiv:1404.2076*, 2014.

[36] Gaurang Patel, Rutvik Mehta, and Upendra Bhoi. Enhanced load balanced min-min algorithm for static meta task scheduling in cloud computing. *Procedia Computer Science*, 57:545–553, 2015.

[37] Carlos A Coello Coello, Gary B Lamont, David A Van Veldhuizen, et al. *Evolutionary algorithms for solving multi-objective problems*, volume 5. Springer, 2007.

[38] Safwat A Hamad and Fatma A Omara. Genetic-based task scheduling algorithm in cloud computing environment. *International Journal of Advanced Computer Science and Applications*, 7(4):550–556, 2016.

[39] Rubén Saborido, Ana B Ruiz, and Mariano Luque. Global wasf-ga: An evolutionary algorithm in multiobjective optimization to approximate the whole pareto optimal front. *Evolutionary computation*, 25(2):309–349, 2017.

[40] B Muthulakshmi and Krishnan Somasundaram. A hybrid abc-sa based optimized scheduling and resource allocation for cloud environment. *Cluster Computing*, 22(5):10769–10777, 2019.

[41] Jianen Yan, Hongli Zhang, Haiyan Xu, and Zhaoxin Zhang. Discrete pso-based workload optimization in virtual machine placement. *Personal and Ubiquitous Computing*, 22(3):589–596, 2018.

[42] Mohammad-Hossein Malekloo, Nadjia Kara, and May El Barachi. An energy efficient and sla compliant approach for resource allocation and consolidation in cloud computing environments. *Sustainable Computing: Informatics and Systems*, 17:9–24, 2018.

[43] Alberto Cocaña-Fernández, Luciano Sánchez, and José Ranilla. Improving the eco-efficiency of high performance computing clusters using eecluster. *Energies*, 9(3):197, 2016.

[44] Alberto Cocaña-Fernández, Luciano Sánchez, and José Ranilla. Leveraging a predictive model of the workload for intelligent slot allocation schemes in energy-efficient hpc clusters. *Engineering Applications of Artificial Intelligence*, 48:95–105, 2016.

[45] Sergi Vila, Fernando Guirado, Josep L Lerida, and Fernando Cores. Energy-saving scheduling on iaas hpc cloud environments based on a multi-objective genetic algorithm. *The Journal of Supercomputing*, 75(3):1483–1495, 2019.

[46] Sergi Vila, Fernando Guirado, Josep L. Lerida, and Fabio Verdi. Aplicación del coeficiente de correlación de pearson en cloud computing para la optimización de cpu y ancho de banda. *Actas XXX Jornadas de Paralelismo*, 2019.

[47] Sergi Vila, Josep L Lérida, Fernando Cores, Fernando Guirado, and Fabio L Verdi. Wpsp: A multi-correlated weighted policy for vm selection and migration for cloud computing. In *European Conference on Parallel Processing*, pages 312–326. Springer, 2020.

[48] Sonu Choudhary and Abhay Kothari. Green data center using spearmans ranking algorithm. *International Journal of Computer Science and Information Technologies*, 6(2):1672–1676, 2015.

[49] Seyedhamid Mashhadi Moghaddam, Sareh Fotuhi Piraghaj, Michael O'Sullivan, Cameron Walker, and Charles Unsworth. Energy-efficient and sla-aware virtual machine selection algorithm for dynamic resource allocation in cloud data centers. In *2018 IEEE/ACM 11th International Conference on Utility and Cloud Computing (UCC)*, pages 103–113. IEEE, 2018.

[50] Gang Sun, Dan Liao, Dongcheng Zhao, Zichuan Xu, and Hongfang Yu. Live migration for multiple correlated virtual machines in cloud-based data centers. *IEEE Transactions on Services Computing*, 11(2):279–291, 2015.

[51] Jean Pepe Buanga Mapetu, Lingfu Kong, and Zhen Chen. A dynamic vm consolidation approach based on load balancing using pearson correlation in cloud computing. *The Journal of Supercomputing*, 77(6):5840–5881, 2021.

[52] Anton Beloglazov, Jemal Abawajy, and Rajkumar Buyya. Energy-aware resource allocation heuristics for efficient management of data centers for cloud computing. *Future generation computer systems*, 28(5):755–768, 2012.

[53] Madnesh K Gupta, Ankit Jain, and Tarachand Amgoth. Power and resource-aware virtual machine placement for iaas cloud. *Sustainable Computing: Informatics and Systems*, 19:52–60, 2018.

[54] Dorian Minarolli, Artan Mazrekaj, and Bernd Freisleben. Tackling uncertainty in long-term predictions for host overload and underload detection in cloud computing. *Journal of Cloud Computing*, 6(1):1–18, 2017.

[55] Yaqiu Liu, Xinyue Sun, Wei Wei, and Weipeng Jing. Enhancing energy-efficient and qos dynamic virtual machine consolidation method in cloud environment. *IEEE Access*, 6:31224–31235, 2018.

[56] Maryam Chehelgerdi-Samani and Faramarz Safi-Esfahani. Pcvm. arima: predictive consolidation of virtual machines applying arima method. *The Journal of Supercomputing*, 77(3):2172–2206, 2021.

[57] Mohan Sharma and Ritu Garg. An artificial neural network based approach for energy efficient task scheduling in cloud data centers. *Sustainable Computing: Informatics and Systems*, 26:100373, 2020.

[58] Rajashree Dash and Pradipta Kishore Dash. A hybrid stock trading framework integrating technical analysis with machine learning techniques. *The Journal of Finance and Data Science*, 2(1):42–57, 2016.

[59] Jossy George, Akhil M Nair, and S Yathish. Analysis of market behavior using popular digital design technical indicators and neural network. In *Expert Clouds and Applications*, pages 445–458. Springer, 2022.

[60] Vipul N Rajput, Kartik S Pandya, Junhee Hong, and Zong Woo Geem. A novel protection scheme for solar photovoltaic generator connected networks using hybrid harmony search algorithm-bollinger bands approach. *Energies*, 13(10):2439, 2020.

[61] Daeyong Jung, JongBeom Lim, Heonchang Yu, and Taeweon Suh. Estimated interval-based checkpointing (eic) on spot instances in cloud computing. *Journal of Applied Mathematics*, 2014, 2014.

[62] Radu Alexandru Badea and Eugen Borcoci. Content server saturation avoidance algorithm based on financial analysis techniques. In *2014 22nd Telecommunications Forum Telfor (TELFOR)*, pages 127–130. IEEE, 2014.

[63] Andrew C Harvey and Simon Peters. Estimation procedures for structural time series models. *Journal of forecasting*, 9(2):89–108, 1990.

[64] H Blanco, J Llados, F Guirado, and JL Lérida. Ordering and allocating parallel jobs on multi-cluster systems. In *12th International Conference Computational and Mathematical Methods in Science and Engineering (CMMSE'12)*, volume 1, pages 196–206, 2012.

[65] Héctor Blanco de Frutos et al. *Clusterización de aplicaciones paralelas para su planificación en entornos de cómputo multi-cluster*. PhD thesis, Universitat de Lleida, 2012.

[66] Josep Lluís Lérida Monsó et al. *Meta-planificador predictivo para entornos multicluster no dedicados*. Universitat Autònoma de Barcelona, 2009.

[67] Jordi Mateo Fornés. *Cloud systems and HPC as a service of agroindustry*. PhD thesis, Universitat de Lleida, 2019.

[68] Jordi Vilaplana Mayoral. *Management of Cloud systems applied to eHealth*. PhD thesis, Universitat de Lleida, 2015.

[69] Eloi Gabaldon, Fernando Guirado, Josep Lluis Lerida, and Jordi Planes. Particle swarm optimization scheduling for energy saving in cluster computing heterogeneous environments. In *2016 IEEE 4th International Conference on Future Internet of Things and Cloud Workshops (FiCloudW)*, pages 321–325, 2016.

[70] Eloi Gabaldon, Josep L. Lerida, Fernando Guirado, and Planes Jordi. Multi-criteria genetic algorithm applied to scheduling in multi-cluster environments. *Journal of Simulation*, 9(4):287—295, 2015.

[71] Eloi Gabaldon, Sergi Vila, Fernando Guirado, Josep L Lerida, and Jordi Planes. Energy efficient scheduling on heterogeneous federated clusters using a fuzzy multi-objective meta-heuristic. In *2017 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, pages 1–6. IEEE, 2017.

[72] Raja Wasim Ahmad, Abdullah Gani, Siti Hafizah Ab Hamid, Muhammad Shiraz, Abdullah Yousafzai, and Feng Xia. A survey on virtual machine migration and server consolidation frameworks for cloud data centers. *Journal of network and computer applications*, 52:11–25, 2015.

[73] Chia-Ming Wu, Ruay-Shiung Chang, and Hsin-Yu Chan. A green energy-efficient scheduling algorithm using the dvfs technique for cloud datacenters. *Future Generation Computer Systems*, 37:141–147, 2014.

[74] Nilson Rubens de Moraes Filho. Melhorando o balanceamento de carga em ambientes virtualizados usando a correlação de pearson. Master's thesis, Universidade Federal de São Carlos, 2018.

[75] Anton Beloglazov and Rajkumar Buyya. Optimal online deterministic algorithms and adaptive heuristics for energy and performance efficient dynamic consolidation of virtual machines in cloud data centers. *Concurrency and Computation: Practice and Experience*, 24(13):1397–1420, 2012.

[76] Zhe Wang, Tianzhen Hong, Han Li, and Mary Ann Piette. Predicting city-scale daily electricity consumption using data-driven models. *Advances in Applied Energy*, 2:100025, 2021.

[77] Christophorus Beneditto Aditya Satrio, William Darmawan, Bellatasya Unrica Nadia, and Novita Hanafiah. Time series analysis and forecasting of coronavirus disease in indonesia using arima model and prophet. *Procedia Computer Science*, 179:524–532, 2021.

[78] Georgia Papacharalampous and Hristos Tyralis. Hydrological time series forecasting using simple combinations: Big data testing and investigations on one-year ahead river flow predictability. *Journal of Hydrology*, 590:125205, 2020.

[79] Siqi Shen, Vincent Van Beek, and Alexandru Iosup. Statistical characterization of business-critical workloads hosted in cloud datacenters. In *2015 15th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing*, pages 465–474. IEEE, 2015.

[80] Abhishek Verma, Luis Pedrosa, Madhukar Korupolu, David Oppenheimer, Eric Tune, and John Wilkes. Large-scale cluster management at google with borg. In *Proceedings of the Tenth European Conference on Computer Systems*, pages 1–17, 2015.

[81] Sergi Vila, Fernando Guirado, Josep L Lerida, and Fernando Cores. Cloudlet scheduling in heterogeneous virtual machine cloud environments. *Actas XXIX Jornadas de Paralelismo*, 2018.

[82] Sergi Vila, Fernando Guirado, Josep L Lerida, and Fernando Cores. Multi-objective genetic algorithm for cloudlet scheduling in heterogeneous virtual machine cloud environments. *International Conference on Computational and Mathematical Methods in Science and Engineering CMMSE*, 2018.

[83] Sergi Vila, Nilson Moraes, Fernando Guirado, Josep L Lérida, Fernando Cores, and Fábio L Verdi. Cloud resources reassignment based on cpu and bandwidth

correlation. In *International Conference on Advanced Information Networking and Applications*, pages 1101–1113. Springer, 2020.

[84] Christian Esteve, Fábio L Verdi, and Maurício F Magalhães. Towards a new generation of information-oriented internetworking architectures. In *Proceedings of the 2008 ACM CoNEXT Conference*, pages 1–6, 2008.

[85] André Luiz Beltrami Rocha, Celso Henrique Cesila, Paulo Ditarso Maciel, Sand Luz Correa, Javier Rubio-Loyola, Christian Esteve Rothenberg, and Fábio Luciano Verdi. Cns-aom: Design, implementation and integration of an architecture for orchestration and management of cloud-network slices. *Journal of Network and Systems Management*, 30(2):1–40, 2022.

[86] Ibrahim Afolabi, Tarik Taleb, Konstantinos Samdanis, Adlen Ksentini, and Hannu Flinck. Network slicing and softwarization: A survey on principles, enabling technologies, and solutions. *IEEE Communications Surveys & Tutorials*, 20(3):2429–2453, 2018.