

A Container-Based Cloud Implementation of a Multi-Swarm PSO for Fuzzy Controller Optimization

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Abstract.

The adoption of cloud-native technologies for distributed computing presents a set of unique challenges. It's important to consider the cloud provider features to achieve scalability, fault-tolerance, reproducibility, and cost-effectiveness while maintaining intended functionality. This paper introduces a container-based implementation of a cloud-native multi-population PSO on Amazon's Elastic Container Service and evaluates its solution and performance and scalability. The study examines the impact of the design parameters, such as the number of swarms and the number of worker containers implementing isolated PSO algorithms. Furthermore, the paper proves that the proposed solution is offering a robust alternative for both local and cloud environments. The results underscore the benefits of containerization for cloud-based bioinspired computing.

Keywords. Cloud Computing, Multi-Swarm Optimization, Fuzzy Control

1 Introduction

Cloud computing is becoming a standard way of running computer science experiments. This shift is largely attributed to its cost-effective, pay-as-you-go model, eliminating the hefty upfront investment and ongoing management expenses associated with local computing infrastructures. Furthermore, cloud computing simplifies defining the infrastructure within the code itself, greatly

enhancing the reproducibility of scientific computing results. A basic example of the benefits of having easily reproducible code is the rise of web-based interactive computing platforms such as the Jupyter Notebook project [11] or Google's Colaboratory [3] platforms. When executing the interactive code, in these platforms, we can easily choose to scale the execution environment, using computing resources that greatly exceed what we have in our personal computers. This capability is a key advantage, enabling more complex and resource-intensive operations that go beyond the limitations of our local hardware. A cloud-native implementation of a computational experiment also has the capability of scaling from local execution to a wide range of execution options via cloud computing services like Amazon's AWS or Microsoft Azure. Cloud computing has evolved from hosting monolithic applications on virtual machines executing on remote data centers to other architectures. Presently, prevailing design patterns in cloud computing adhere to the principles of microservices [28] and serverless [31]. Microservices architecture [14] emphasizes breaking down applications into smaller, loosely-coupled components, fostering flexibility and scalability. On the other hand, serverless computing further refines this paradigm by abstracting away infrastructure concerns, enabling developers to focus solely on code execution and minimizing resource allocation to

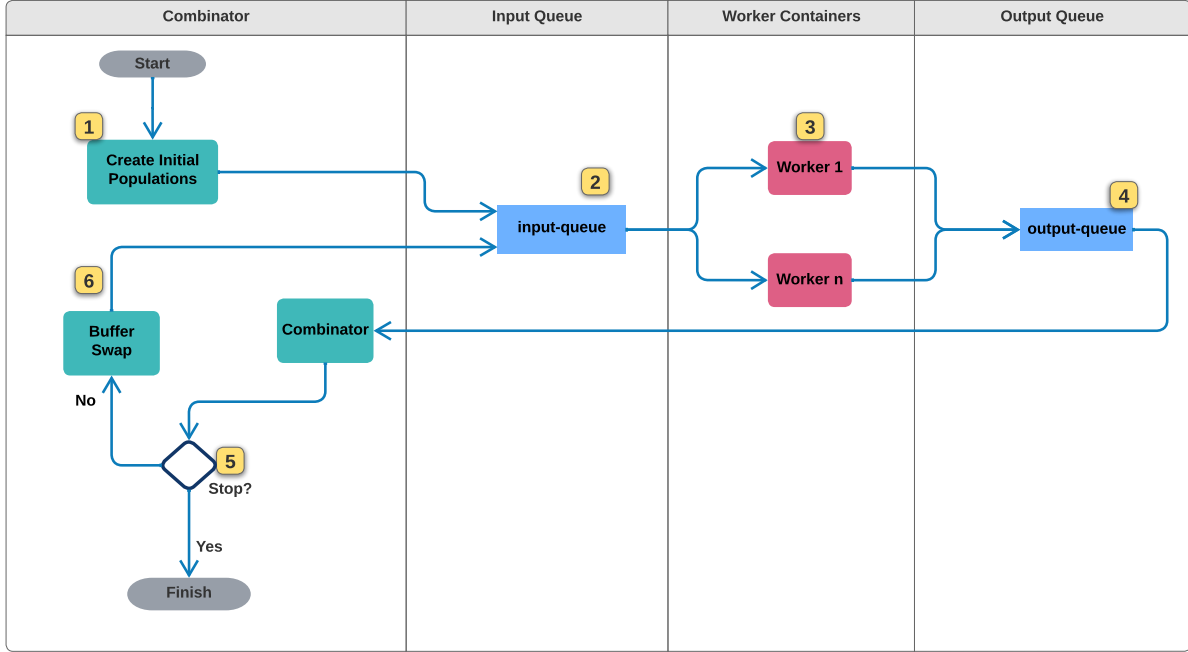


Fig. 1. Container-based architecture proposed by García-Valdez and Merelo [29] in which multiple swarms are created and added to an input-queue, multiple workers then evolve these swarms, and finally, they migrate in the combinator process. This cycle is repeated several times. The dynamic adaptation of C1 and C2 is executed each time a swarm reaches the combinator.

match application demands dynamically. The combined use of these design patterns enhances the efficiency and adaptability of computational experiments in cloud-native environments.

Cloud-native applications bring new methodologies and techniques [1]. To better exploit the capabilities of the cloud infrastructure, applications are implemented as reactive systems [2] that are generally more scalable, flexible, and fault-tolerant; these can be implemented as a loosely coupled collection of microservices.

These components are easily implemented and deployed to cloud environments, where processing nodes can be defined and deployed using scripts, and scalable message queue services are provided to easily send and receive events. Additionally, scalability in such systems is achieved through the automatic provisioning of additional computing nodes as demand increases or in

response to node failures, ensuring consistent performance and reliability.

Microservices are typically executed within isolated runtime environments called containers [?]. These containers do more than just provide a runtime environment; they encapsulate all the necessary components required for the microservice to function autonomously. This includes software libraries, binaries, and configuration files. Essentially, containers package everything that a node needs to operate. The strength of a containerized application lies in its ease of operation on automation platforms. These platforms are capable of taking containerized microservice-based applications from a local computer to be deployed in a cloud or an ephemeral infrastructure [10, 12].

In our previous research [21], we highlighted that a reactive architecture is well-suited for

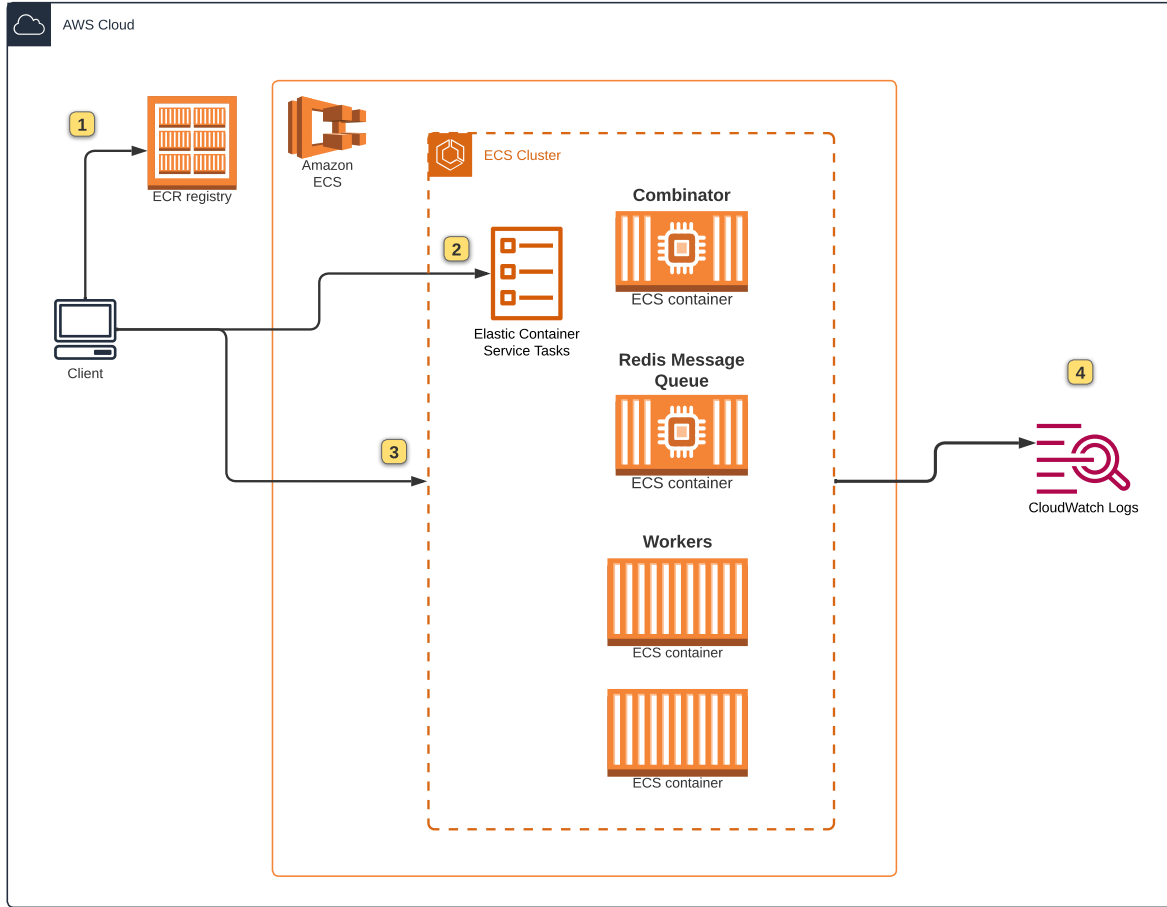


Fig. 2. Implementation using AWS cloud technologies

implementing population-based metaheuristics if they require extensive computational resources. Building on this foundation, the current work details the deployment process of a reactive, container-based, multi-swarm PSO algorithm specifically designed for deployment in Amazon's AWS. The optimization problem tackled in this work is presented in [17] and consists of tuning the membership functions of a fuzzy controller. This optimization problem is computationally intensive, primarily because it requires evaluating the fitness of all potential solutions. This evaluation process involves running multiple simulations for each candidate solution, as further explored in [18,

19]. Despite the computational demands of this optimization problem, the independent nature of solution evaluation in evolutionary algorithms allows for the efficient parallelization of work. In the literature, we found only a few works [5, 23, 4] attempting to distribute fuzzy controller's optimization; however, these works have not fully leveraged the advancements in cloud-native technologies.

This gap presents an opportunity to explore how modern cloud-native solutions can enhance population-based optimization. This examination focuses on the intricacies of deploying such an algorithm within a cloud environment, leveraging

the scalability and flexibility of AWS services. The use of containerization, a key feature of this deployment, offers the benefit, of having environment consistency and ease of scalability. This approach aligns with the principles of reactive systems, ensuring that the deployed algorithm is efficient in resource usage and robust and adaptable to varying computational loads.

In summary, our approach addresses a fuzzy control problem through the application of a cloud-native distributed Particle Swarm Optimization (PSO) algorithm, characterized by its minimal set of tunable parameters. We emphasize the significance of our design choices and elucidate the deployment process leveraging various cloud technologies provided by Amazon's AWS.

This paper is dedicated to a cost analysis, comparing multiple configurations of both local and cloud deployments. By scrutinizing the associated costs, we aim to provide insights into the economic considerations associated with implementing our proposed solution in different computing environments.

We organized the paper as follows: First, Section 2 presents state of the art relevant to our work. In Section 3, we present the proposed method and the container-based cloud deployment in Section 4 we present the use case and experimental setup to assess deployment options, concerning time-to-solution performance, discussing the results in Section 5. Finally, we offer the conclusions and suggestions for future work in Section 6.

2 Related Work

One of the primary features that make containers interesting is their ephemeral nature: fast startup and tear-down time make them usable for machine-independent and cloud deployment of simple, ephemeral, and sometimes stateless functions. Furthermore, containerization, facilitated by orchestration engines such as Docker Swarm or Kubernetes, as well as non-self-scaling specifications like `docker-compose`, enables the explicit definition of relationships between different components or services within an application. This orchestration capability empowers developers to

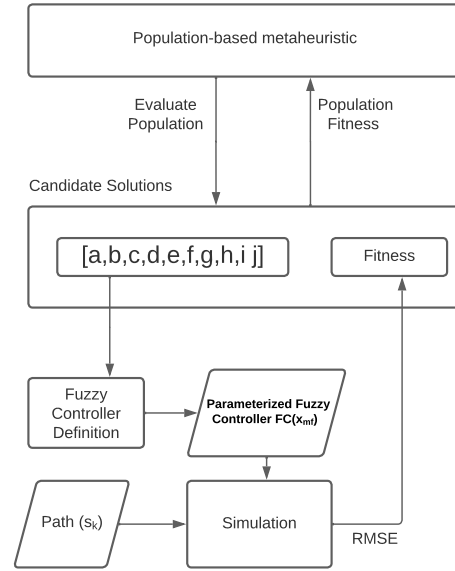


Fig. 3. Fuzzy Controller Problem [18].

articulate the intricate interdependencies within their applications.

The realization of Docker-based architectures [12] has given rise to a set of patterns that collectively delineate the landscape of cloud-native application development.

The integration of cloud-based evolutionary algorithms into cloud computing has been a gradual evolution within the field. Two notable examples in the integration of evolutionary algorithms with cloud computing include the Offspring framework developed by Vecchiola et al. [32] and the FlexGP system by Sherry et al. [27]. The Offspring framework implements a multiobjective Evolutionary Algorithm (EA) designed to operate on Aneka Enterprise Clouds. The system is built on top of a task model with a plugin architecture, enhancing its flexibility and extensibility. On the other hand, the FlexGP system is a pioneering large-scale Genetic Programming (GP) system designed for cloud deployment. It adopts an Island model approach and is specifically implemented on Amazon EC2, utilizing a socket-based client-server architecture. Furthermore, Valenzuela and García-Valdez [30] implemented a pool-based

Table 1. Cost AWS

Service	Price	Free tier
Elastic Container Registry		
Storage	\$0.10 per GB	50 GB
All data transfer IN	\$0.00 per GB	
Data Transfer OUT		
Next 9.999 TB / month	\$0.09 per GB	
AWS Fargate		
per vCPU per hour	\$0.040480	20 GB
per GB per hour	\$0.004445	
Fargate Ephemeral	\$0.000111	
Storage GB per hour		
Amazon Cloud Watch		
Collect (Data Ingestion)		
Standard	\$0.50 per GB	0 to 5 GB
Infrequent Access	\$0.25 per GB	0 to 5 GB

evolutionary algorithm using EC2 instances as workers, using a distributed pool for asynchronous collaboration between workers. Another feature of cloud computing is to provide infrastructure as a service (IaaS).

Several works starting to use these platforms, EvoSpace [9] used the PiCloud platform. PiCloud was a cloud to developers for running Python-based applications and tasks. It was designed to simplify the deployment and scaling of Python code in the cloud. Similar steps were taken by Salza and Ferrucci [25, 26] when they proposed an architecture to extend the reach of evolutionary algorithms into the cloud. This pioneering work laid the foundation for subsequent developments, as demonstrated in their subsequent paper [6].

The mentioned papers mark a transition toward incorporating cloud-native elements into the domain of evolutionary algorithms. Notably, they introduced aspects like the integration of messaging queues and the adoption of CoreOS as an operating system specifically tailored for efficient container utilization in evolutionary algorithms. However, it's worth noting that despite the infusion of cloud-native features, the management of containers in these instances still adheres to a more traditional approach from the perspective of distributed Evolutionary Computing (EC). Specifically, a master-worker architecture is employed, with communication facilitated through RabbitMQ, a messaging queue. In this setup,

replicated workers are responsible for executing tasks in parallel, aligning with the distributed nature of EC methodologies.

While the papers introduce cloud-native elements, the underlying container management strategy retains a classical distributed EC framework, emphasizing the orchestration of tasks through a master node and distributed workers communicating via a messaging queue. This hybrid approach leverages both cloud-native technologies and established EC paradigms to enhance the scalability and efficiency of evolutionary algorithms in distributed environments. Dziurzanski et al. [7] implements an island model using a container-based architecture.

Pool-based systems [20, 22] are closer to serverless systems [14], as they pull populations from the pool and run whole algorithms, instead of just doing the evaluation. The pool is a shared data storage for results and can be accessed in an asynchronous way, which suits better the nature of cloud-native systems.

Other population-based metaheuristics also have multi-population versions. For instance, there are many proposals on Multi-Swarm Optimization methods [13] for the PSO algorithm; however, because the PSO algorithm is based on position, velocity, and distance between particles, researchers put more effort into the topology of communication between swarms.

3 Cloud-based Deployment

Figure 1 shows the container-based architecture proposed by García-Valdez and Merelo [29, 8] the multi-swarm design. We adapted this initial design, adding components and strategies that are presented in previous papers. Adapting the initial parameters of the algorithm to use an heterogeneous strategy [16] together with an adaptation of these parameters considering the diversity and the number of iterations of the algorithm. In these previous works we implemented the event-driven design using containers running locally in a single workstation.

Before explaining in detail the cloud deployment, we first explain the overall design. Figure 1 shows the main components of the system as

Table 2. Experimental Setup

Algorithm	Parameter	Range [min,max]
MS-PSO	Communication Topology	Fully connected
	Speed.	Min=[-0.20, -0.30] Max=[0.20, 0.30]
	Cognitive and Social C_1, C_2	[1.0, 2.0]
Cloud	Size	10
	Swarms	36 or 40
	Iterations	4
	Cycles	10
	Dimensions	15
	# Function Evaluations	14400 or 16000
Local	Size	10
	Swarms	16
	Iterations	8
	Cycles	10
	Dimensions	15
	# Function Evaluations	12,800

swim lanes. Following an event-driven design, we have two processing components (`combinator` and `worker`) that communicate via message queues. The data passed and interchanged between components are swarms (or populations) containing the current state of the proposed solutions (in these case particles). Decoupling the population state from the search algorithm presents several advantages, we can scale the system by adding new populations and we can even have multiple algorithms processing the populations. In the current implementation we opted for having a single PSO algorithm for processing all the populations. This is then a Multi-Swarm PSO.

The `combinator` process has other responsibilities, but is initially responsible for the first step, that is, creating a certain number of swarms, with each particle is randomly positioned in the search space. Together with the collection of particles the initial parameters of the PSO algorithm are also generated randomly generated with in a range of values. This is called a heterogeneous strategy, this strategy gives acceptable results without the burden of searching the parameters experimentally [15]. As a second step (2), the data for each swarm is packed in a message in JSON format and pushed to the `input-queue`. The queue

is constantly consumed by `Worker Containers`. We can have many workers, each worker is a daemon process that takes one message at a time from the `input-queue` (3), reads the PSO parameters contained in the message and then runs the specified number of iterations on the received swarm. In local PSO algorithm there is not an initialization step, the algorithm takes the current state of the swarm, and starts the iteration. After several iterations the resulting state of the swarm is pushed to the `output-queue` (4). The `combinator` process pulls the resulting swarm messages, and checks first if the best solution has been found (5), if this is true the algorithm ends. If not, the best solutions are kept in a buffer with the best k individuals. Then the swarm data is stored in a buffer. If the buffer has a certain number of swarms (in this case two) the populations are combined swapping particles between the two in a process similar to a one-point crossover (6). This process is similar to the migration step of other Multi-swarm PSO algorithms. Before sending the modified swarms and depending on the current state of the algorithm a fuzzy system adapts the $C1$ and $C2$ parameters of the swarms and pushes the newly generated swarms again to the `input-queue` starting a new cycle.

We mentioned earlier that we have several

Table 3. Function Evaluations per second comparison between local and three configurations on AWS Elastic Container Service

	<i>Local</i>	<i>AWS Elastic Container Service</i>		
Configuration	Mac Studio	1	2	3
Workers	16	36	36	40
Swarms	10	36	40	36
#FE	12800	14400	16000	14400
RMSE	0.00271	0.00328	0.00404	0.00303
Time in seconds	754.9677	840.660	1059.593	936.064
Evals. per second	16.954	17.129	15.100	15.383
Cost per run (USD)		0.4524	0.570	0.559

options for the deployment of cloud-native application to AWS, the most common approach is to use single or several virtual servers using EC2 instances. In our current deployment we opted for using Amazon Elastic Container Service (ECS). ECS is a fully-managed container orchestration service, it allows the user to run, stop, and manage Docker containers on a cluster, simplifying the process of deploying, managing, and scaling containerized applications. ECS uses *Task Definitions* as a blueprint for a set of containers that run together on the same host. It defines parameters such as which Docker images to use, the CPU and memory requirements, networking information, among others. A task definition is similar to a `docker-compose` file in the sense that defines the interaction of several containers. To minimize the need to manage the underlying infrastructure, we use what is called *Fargate Tasks*, this is a serverless compute engine that eliminates the need for launching and managing EC2 instances directly. We only need to specify the resource requirements needed for our task.

Figure 2, shows the main cloud computing technologies from Amazons AWS we used in the deployment of the multi-swarm algorithm. For each of the components described previously, we had specified a Docker container definition using a `Docker` file. With this Docker definition we could run the algorithm locally using a `docker-compose` script. As a first step for a cloud deployment we need to create a repository for each container definition in Amazon Elastic Container Registry

(ECR) (1). ECR is a fully-managed container registry service provided by AWS. This registry is used to store, manage, and deploy Docker container images. The advantage of having an image repository is that we can keep several versions of each image. As a second step (2), we defined a *Fargate Task Definition* for each component. We then created a ECS cluster, an ECS cluster is a logical grouping of container instances or tasks on which we can run our containerized applications. We now run the Task Definitions (3), and observe the logs of the execution in Amazon CloudWatch, this is a monitoring and observability service. These steps can be realized using a browser-based user interface or using command-line interface.

Each of the services mentioned above has a cost that is charged monthly, the current prices are shown in Table 1. First, we need to consider the cost of storing the Docker container images in the ECR. We have 50GB a month for free, but is important to remember that some container images can grow to several GB depending on the operating system, languages, libraries, and software included in the container. The data transfer cost for a private registry is negligible, there is no cost for uploading the images, and there is no data transfer to the outside. When we specify the computing resources for running a certain *Fargate Task*, we select the number of vCPUs to assign and depending on our selection there is a minimum and maximum amount of memory we can assign to the task. At this time, when selecting

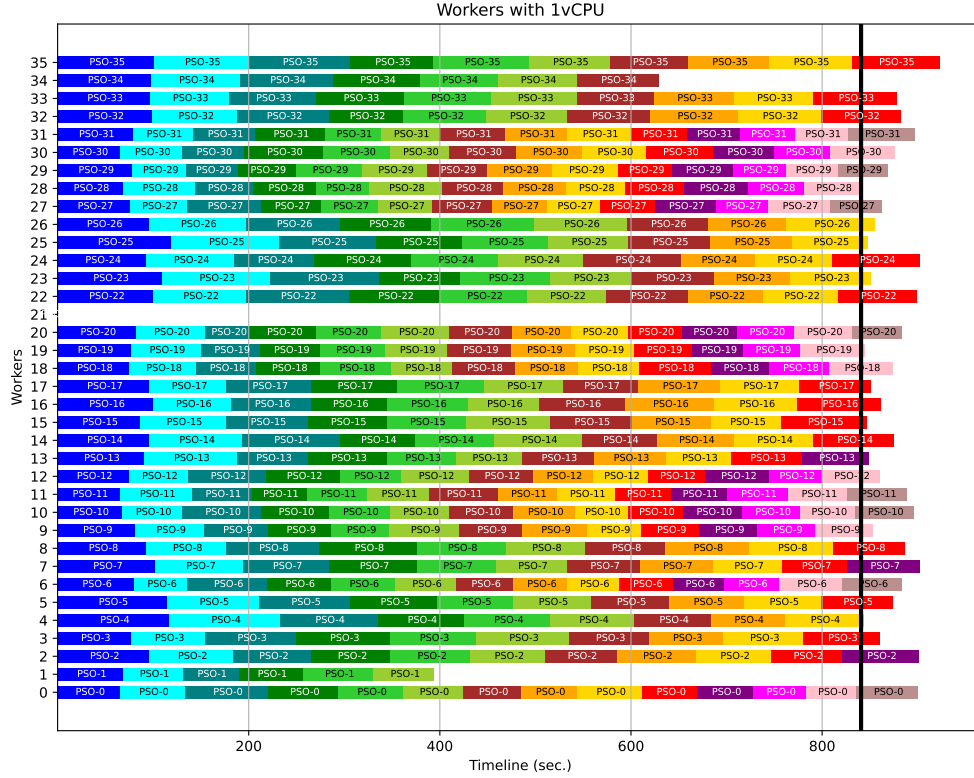


Fig. 4. Execution of 36 workers and 36 swarms, The timeline at the bottom marks the progression in seconds, indicating the duration of each PSO instance's activity inside a particular worker container.

1 vCPU the minimum memory is 2 GB and the maximum 8 GB, in 1 GB increments. We selected 3 GB memory for our containers. For running these experiments, we did not need additional ephemeral storage, we used the 20 GB included for free. Finally, we used the CloudWatch service extensively, to keep track of the algorithm and to summarize the results.

4 Use Case

To test the deployment we are comparing the time of execution of three configurations running on Amazon's Elastic Container Service against a local execution using a Mac Studio workstation. We describe next the resource intensive optimization problem used as proof-of-concept.

In this case, we want to optimize the membership functions for a fuzzy controller for a rear-wheel controller [24]. The fuzzy controller is presented in a previous paper [19]. This problem was selected because it consumes extensive computational resources for the evaluation of candidate solutions. Figure 3 details the evaluation components for each candidate solution. Each solution consists of a list of real parameters for establishing the components of the membership functions for a fuzzy controller definition. With this definition we create a controller instance, we then simulate the control by following several paths with different degrees of difficulty. We then calculate the average of the RMSEs obtained for each path. This average is considered the fitness of the candidate solution. If a controller is not capable of following the track to a certain degree the simulation is terminated and that controller is assigned the worst fitness value

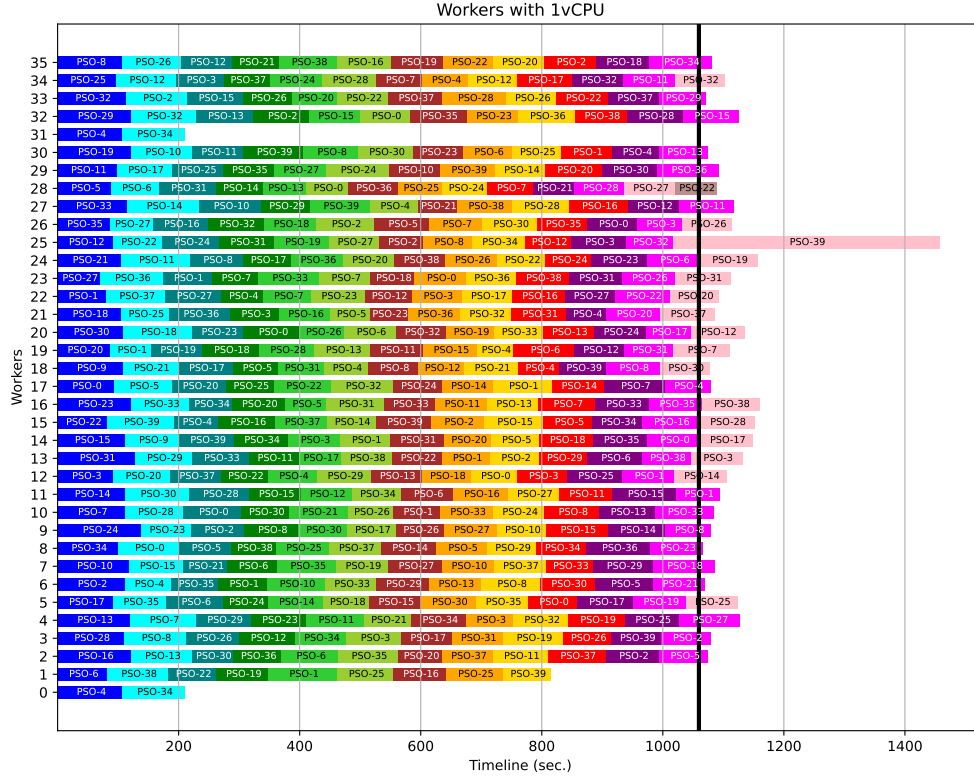


Fig. 5. Execution of 36 workers and 40 swarms. The timeline at the bottom marks the progression in seconds, indicating the duration of each PSO instance's activity inside a particular worker container.

(RMSE=5000).

The current implementation uses the Python language, this means that even if there are multiple CPUs in the computer, the Python interpreter process's uses only a single thread or CPU at a time. For this reason, we only run workers in Fargate instances using a single vCPU. Each vCPU is a hyperthread of an Intel Xeon CPU core. We validated this by running a few experiments using instances with 4vCPUs but we did not found a substantial difference in the compute time, so the additional cost is not justified.

For the cloud configurations we compare use two configurations: 36 and 40 workers. This means 36 and 40 vCPUs This number of processors is higher than what we normally find in a PC Workstation. We are comparing the results with a local implementation using a high-end workstation, in this case a 2022 Mac Studio with an Apple

M1 Ultra chip with 20 CPUs (16 performance and 4 efficiency). We use 16 workers in this configuration to fully exploit the maximum number of performance cores.

We normally set the number of swarms and the number of workers with a similar value, if we increase the number of swarms, many will remain in the input-queue waiting for a worker to be available. If we have more workers than swarms, the situation is worst, because now we will have workers waiting for swarm to be available. To test how much the ratio of swarms/workers affects the time of execution we test with these three configurations: the same number of swarms and workers with 36 each, 36 workers and 40 swarms, and finally 40 workers and 36 swarms.

The multi-swarm is composed of 36 or 40 swarms with ten particles each, although this is a small size for a traditional single swarm PSO, in

the case of a MS-PSO the total size of the swarm is the sum of all swarms. Each local PSO will run four iterations of the algorithm before returning the resulting swarm state to the `output-queue`. All swarms will complete ten cycles, meaning they will go through the combiner and back to the `input-queue` a total of ten times each.

The parameters of the multi-swarm version of the PSO algorithm are shown in Table 2. To compare the time-to-solution performance we use as a metric the number of function evaluations per second (EPS). As we mentioned before, the fitness evaluation function is the most computationally demanding component of the PSO algorithm, and this is why the number of calls to this function is a commonly used metric to evaluate the amount of work needed to find a solution independently of the parameters or hardware used. In this case, we change the parameters of the MS-PSO algorithm, depending on the amount of swarms and workers available. These changes in the configuration yield different numbers of function evaluations for each configuration. To take this into account, we compare the speed of execution by EPS and higher values are better.

5 Results

Table 3 shows the results for the proposed configurations, giving the best RMSE obtained, the total time (in seconds) and the function evaluations per second of the experiments. We also included the cost per execution according to the number of workers and the time to finish, considering only the vCPU and Memory costs. We can see that there is a significant increase in the #FE per second when the number of swarms is equal to the number of workers. These results can be explained by analyzing the timeline of three representative runs.

First, we describe the format in which the results are presented. Figures 4 to 6 shows the timelines for the proposed configurations. The x-axis shows the time elapsed in seconds from the beginning of the experiment. Each row represents a particular worker, identified by a sequential number. Each box represents the range of time in seconds, beginning when a swarm is pulled from the `input-queue` until is pushed to the `output-queue`.

Each swarm is identified by a sequential integer. The elapsed time is not the same in all cases, because depending on the performance of the controller the time to complete the path is different. Also, when the error or distance to the path is large the simulation is interrupted thus taking less time. To identify each swarm, the color corresponds to the order in which it was received in each worker, this is to avoid those cases where the same swarm is sequentially received by the same worker twice. In this case, if the swarm is of the same color it is difficult to distinguish between the two boxes. The vertical bold line indicates the moment in time when the number of evaluations has been reached. At this moment, no more swarms are pushed to the `input-queue`. Because workers, take swarms asynchronously, the work that was already in the `input-queue` is still pulled by workers, and the work they are processing at that time is also finished. This is why more work is processed beyond the bold line.

Figure 4 shows the timeline for the experiment using 36 workers and 36 swarms. When we have this configuration it is very common that each swarm is executed exclusively by the same worker. This is because the `input-queue` will be empty most of the time. Once a worker finishes the processing of a certain swarm it will be available for the next swarm in the `input-queue`. The combinator returns the same swarm to the `initial-queue` and the same worker is available to take the same swarm again. Furthermore, when this condition happens, there is not a noticeable waiting time for workers. We can see that this happens in all the workers. Is important to notice that *worker 21* takes a swarm, but this swarm is never pushed back in to the `output-queue`. This could be because there was an error in the swarm configuration or a bug in the code. At this moment, we do not have a fault-tolerant solution, for instance, to restart a worker if the work is not returned after certain amount of time. But in any case, the nature of the event-driven solution still works well in this cases. The extra work needed to reach the number of evaluations needed to complete the experiment is distributed among all the other workers. Figure 5 show the case when we have more swarms than workers, as a

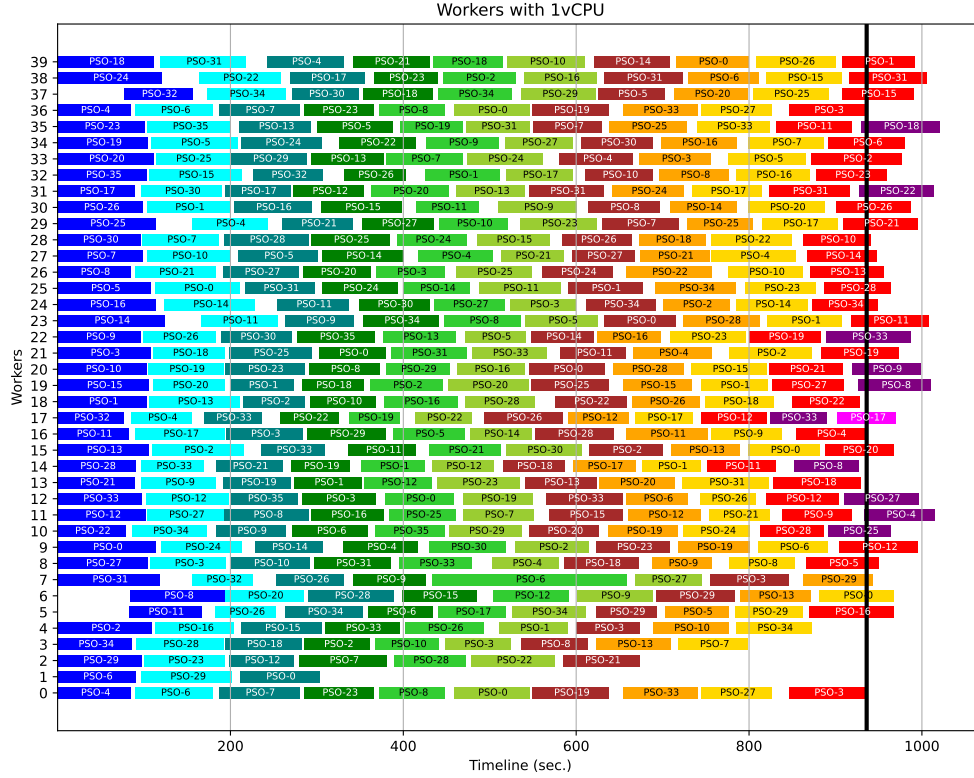


Fig. 6. Execution of 40 workers and 36 swarms. The timeline at the bottom marks the progression in seconds, indicating the duration of each PSO instance's activity inside a particular worker container.

consequence, swarms are not always processed by the same worker like in the previous case. We need to assess in a future work if this behavior is beneficial to the search algorithm. The drawback of this case is that the work takes more time because we have less resources to do the computation. Finally, Figure 6 shows the case in which we have spare workers. The problem with this approach is that the workers have to wait until a new population is available, for example *worker 5* needs to wait until a swarm is available. In this case, population PSO-11 is received by *worker 5* after *worker 16* finished working on the swarm. Nevertheless, even if we have more computing resources, because of the addition idle time of the workers the overall time is not the best.

When comparing against the local execution, results show that we needed about 2.25 times the number of workers to match the time-to-finish

performance of a local execution. There are several factors that could have an impact on this difference, the communication time for a local container network is faster than in a cloud environment, the M1 chip tied with a fast memory bandwidth (800GB/s) are faster than a vCPU, there could be differences in the virtualization environment in which the docker host runs, the Docker engine used in Mac Studio is optimized for the M1 chip. On the other hand, running these type of experiments in a cloud environment does not incur in an initial investment on a workstation computer.

6 Conclusion and Future Work

This paper gives details on the cloud-native design and deployment options for a multi-swarm

PSO algorithm. The algorithm addresses the computationally demanding optimization problem of tuning the membership functions of a fuzzy controller applied on rear-wheel path tracking. We deployed the algorithm on Amazon's container platform, and compare this solution against a local docker based deployment. We compared the three different configurations to highlight the differences between worker and swarm ratios. We found that the most effective configuration is to have a configuration with the same number of workers or threads and swarms. We found that for certain use cases, the number of workers needs to be increased when deploying the algorithm to a cloud provider. Cloud deployment of cloud-native implementation of population-based algorithms is cost effective alternative with out the need of investing on additional hardware or administrative costs.

For future research, we aim to expand upon the design options, on the algorithmic side and as well as the deployment on the cloud. On the algorithm, we can dynamically change the size or number of swarms (and workers) to ascertain potential performance gains. When implementing these options we can test the auto-scaling features of the cloud platform, with the intent to optimize resource utilization with out degrading the the algorithm's exploratory capacities.

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References

1. Baldini, I., Castro, P., Cheng, P., Fink, S., Ishakian, V., Mitchell, N., Muthusamy, V., Rabbah, R., & Suter, P. (2016). Cloud-native, event-based programming for mobile applications. *Proceedings - International Conference on Mobile Software Engineering and Systems, MOBILESoft 2016*, pp. 287–288.
2. Bonér, J., Farley, D., Kuhn, R., & Thompson, M. (2014). The reactive manifesto.
3. Carneiro, T., Da Nóbrega, R. V. M., Nepomuceno, T., Bian, G.-B., De Albuquerque, V. H. C., & Reboucas Filho, P. P. (2018). Performance analysis of google colab as a tool for accelerating deep learning applications. *IEEE Access*, Vol. 6, pp. 61677–61685.
4. Ciurea, S. (2013). Determining the parameters of a sugeno fuzzy controller using a parallel genetic algorithm. *2013 19th International Conference on Control Systems and Computer Science*, IEEE, pp. 36–43.
5. Cortes-Rios, J. C., Gómez-Ramírez, E., Ortiz-de-la Vega, H. A., Castillo, O., & Melin, P. (2014). Optimal design of interval type 2 fuzzy controllers based on a simple tuning algorithm. *Applied Soft Computing*, Vol. 23, pp. 270–285.
6. De Lucia, A. & Salza, P. (2017). *Parallel Genetic Algorithms in the Cloud*. Ph.D. thesis, University of Salerno.
7. Dziuranski, P., Zhao, S., Przewozniczek, M., Komarnicki, M., & Indrusiak, L. S. (2020). Scalable distributed evolutionary algorithm orchestration using docker containers. *Journal of Computational Science*, pp. 101069.
8. García-Valdez, J.-M. & Merelo-Guervós, J.-J. (2018). A modern, event-based architecture for distributed evolutionary algorithms. *Proceedings of the Genetic and Evolutionary Computation Conference Companion*, pp. 233–234.
9. García-Valdez, M., Trujillo, L., Merelo, J.-J., De Vega, F. F., & Olague, G. (2015). The evospace model for pool-based evolutionary algorithms. *Journal of Grid Computing*, Vol. 13, No. 3, pp. 329–349.
10. Gilbert, J. (2018). *Cloud Native Development Patterns and Best Practices: Practical architectural patterns for building modern, distributed cloud-native systems*. Packt Publishing Ltd.
11. Kluyver, T., Ragan-Kelley, B., Pérez, F., Granger, B. E., Bussonnier, M., Frederic, J., Kelley, K., Hamrick, J. B., Grout, J., Corlay, S., et al. (2016). Jupyter notebooks-a publishing format for reproducible computational workflows. *Elpub*, Vol. 2016, pp. 87–90.
12. Kratzke, N. & Quint, P.-C. (2017). Understanding cloud-native applications after 10 years of cloud computing-a systematic mapping study. *Journal of Systems and Software*, Vol. 126, pp. 1–16.

13. Ma, H., Shen, S., Yu, M., Yang, Z., Fei, M., & Zhou, H. (2019). Multi-population techniques in nature inspired optimization algorithms: a comprehensive survey. *Swarm and evolutionary computation*, Vol. 44, pp. 365–387.
14. Malawski, M., Gajek, A., Zima, A., Balis, B., & Figiela, K. (2020). Serverless execution of scientific workflows: Experiments with hyperflow, aws lambda and google cloud functions. *Future Generation Computer Systems*, Vol. 110, pp. 502 – 514.
15. Mancilla, A., Castillo, O., & García-Valdez, M. (2023). Optimization of fuzzy controllers using distributed bioinspired methods with random parameters. In *Hybrid Intelligent Systems Based on Extensions of Fuzzy Logic, Neural Networks and Metaheuristics*. Springer, pp. 189–197.
16. Mancilla, A., Castillo, O., & García-Valdez, M. (2024, to be published). Fuzzy adaptation of parameters in a multi-swarm particle swarm optimization (pso) algorithm applied to the optimization of a fuzzy controller. In *New Horizons for Fuzzy Logic, Neural Networks and Metaheuristics*. Springer, pp. .
17. Mancilla, A., Castillo, O., & Valdez, M. G. (2021). Optimization of fuzzy logic controllers with distributed bio-inspired algorithms. *Recent Advances of Hybrid Intelligent Systems Based on Soft Computing*, pp. 1–11.
18. Mancilla, A., Castillo, O., & Valdez, M. G. (2022). Evolutionary approach to the optimal design of fuzzy controllers for trajectory tracking. *Intelligent and Fuzzy Techniques for Emerging Conditions and Digital Transformation*, Springer International Publishing, Cham, pp. 461–468.
19. Mancilla, A., García-Valdez, M., Castillo, O., & Merelo-Guervós, J. J. (2022). Optimal fuzzy controller design for autonomous robot path tracking using population-based metaheuristics. *Symmetry*, Vol. 14, No. 2, pp. 202.
20. Merelo, J. J., Fernandes, C. M., Mora, A. M., & Esparcia, A. I. (2012). Sofea: a pool-based framework for evolutionary algorithms using couchdb. *Proceedings of the 14th annual conference companion on Genetic and evolutionary computation*, ACM, pp. 109–116.
21. Merelo, J. J., Laredo, J. L. J., Castillo, P. A., García-Valdez, J.-M., & Rojas-Galeano, S. (2019). Scaling in concurrent evolutionary algorithms. *Workshop on Engineering Applications*, Springer, pp. 16–27.
22. Merelo-Guervós, J. J., Mora, A., Cruz, J., Esparcia-Alcázar, A., & Cotta, C. (2012). Scaling in distributed evolutionary algorithms with persistent population. *Evolutionary Computation (CEC), 2012 IEEE Congress on*, pp. 1 –8.
23. Oh, S.-K., Jang, H.-J., & Pedrycz, W. (2009). The design of a fuzzy cascade controller for ball and beam system: A study in optimization with the use of parallel genetic algorithms. *Engineering Applications of Artificial Intelligence*, Vol. 22, No. 2, pp. 261–271.
24. Paden, B., Čáp, M., Yong, S. Z., Yershov, D., & Frazzoli, E. (2016). A survey of motion planning and control techniques for self-driving urban vehicles. *IEEE Transactions on intelligent vehicles*, Vol. 1, No. 1, pp. 33–55. Publisher: IEEE.
25. Salza, P. & Ferrucci, F. (2016). An approach for parallel genetic algorithms in the cloud using software containers. *arXiv preprint arXiv:1606.06961*.
26. Salza, P., Ferrucci, F., & Sarro, F. (2016). Develop, deploy and execute parallel genetic algorithms in the cloud. *Proceedings of the 2016 on Genetic and Evolutionary Computation Conference Companion*, pp. 121–122.
27. Sherry, D., Veeramachaneni, K., McDermott, J., & O'Reilly, U. M. (2012). Flex-GP: Genetic programming on the cloud. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, Vol. 7248 LNCS, pp. 477–486.
28. Thönes, J. (2015). Microservices. *IEEE Software*, Vol. 32, No. 1, pp. 116–116.
29. Valdez, M. G. & Guervós, J. J. M. (2021). A container-based cloud-native architecture for the reproducible execution of multi-population optimization algorithms. *Future Generation Computer Systems*, Vol. 116, pp. 234–252.
30. Valenzuela, R. M. & Valdez, M. G. (2015). Implementing pool-based evolutionary algorithm in Amazon Cloud Computing Services. In *Design of Intelligent Systems Based on Fuzzy Logic, Neural Networks and Nature-Inspired Optimization*. Springer, pp. 347–355.
31. Varghese, B. & Buyya, R. (2018). Next generation cloud computing: New trends and research directions. *Future Generation Computer Systems*, Vol. 79, pp. 849–861.
32. Vecchiola, C., Kirley, M., & Buyya, R. (2009). Multi-objective problem solving with offspring on enterprise clouds. *arXiv preprint arXiv:0903.1386*.

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