

A Performance Modeling Showcase

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ABSTRACT

As computing is getting more ubiquitous in our lives, modern software applications and computer infrastructures are getting increasingly complex and require huge financial investments. In this context, knowing how to design, redesign and optimize computer systems and networks is one of the most important skills for software engineers because it can guarantee companies a competitive advantage, both in terms of technology and investment.

In this technical report we propose a next-event simulation model to analyze the performance of a two-layer Cloud system that leverages an off-loading policy to minimize response-time. First, we describe how we have implemented the multi-stream pseudo-random number generator, that is a fundamental building block of any next-event simulation. Then, we describe the performance model in terms of goals, conceptual, specification, computational model and verification.

The experimental results show (i) the satisfactory randomness degree of the adopted pseudo-random number generator and (ii) the effectiveness of our model to tune the system as to achieve better performance. Although the promising results, we conclude our work delineating possible improvements for our model.

CCS CONCEPTS

• **Networks** → **Network simulations; Network performance analysis**; • **Theory of computation** → **Random walks and Markov chains**;

KEYWORDS

performance modeling; simulation tools

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1 INTRODUCTION

As computing is getting more ubiquitous in our lives, modern software applications and computer infrastructures are getting increasingly complex and require huge financial investments. In

this context, knowing how to design, redesign and optimize computer systems and networks is one of the most important skills for software engineers because it can guarantee companies a competitive advantage, both in terms of technology and investment. In this technical report we propose a next-event simulation model to analyze the performance of a two-layer Cloud system that leverages an off-loading policy to minimize response-time.

The remainder of the paper is organized as follows. In Section 2 we describe the pseudo-random number generator adopted to generate random variates for the next-event simulation model. In Section 3 we describe the next-event simulation model in terms of goals, conceptual, specification, computational model and verification. In Section 4 we show the experimental results about the randomness of the adopted pseudo-random number generator and the performances recorded by our model. In Section 5 we show how to configure and run experiments and some sample outputs to provide a better idea of what has been created. In Section 6 we conclude the paper summing up the work that has been done.

2 RANDOM NUMBER GENERATION

The generation of pseudo-random numbers is a fundamental building-block for next-event simulations. In fact, a sequence of pseudo-random numbers uniformly distributed in $(0, 1)$ can be used to generate stochastic variates, e.g. the exponential distribution, that can be leveraged to generate random stream of events, e.g. requests to the system with random occurrence time and computational demand. There exist many techniques for random number generation, a lot of which are comprehensively presented in [3]. The most notable algorithmic generators are *multiple recursive generators*, *composite generators*, and *shift-register generators*. Although all of these produce periods wider than the one produced by a Lehmer generator, they also have a sensible cost in terms of computational complexity.

In this work we adopted a multi-stream Lehmer generator (a, m, s) , which is defined by the following equation,

$$x_{i+1} = (a^j \bmod m)x_i \bmod m \quad \forall j = 0, \dots, s-1 \quad (1)$$

where m is the modulus, a is the multiplier, s is the number of streams and $(a^j \bmod m)$ is the jump multiplier.

We have chosen this solution because (i) it provides a great degree of randomness with the appropriate parameters (ii) the multi-streaming is required by simulations with multiple stochastic components (iii) it is a de-facto standard, hence it is easy to compare our experimental results with the one provided in literature.

We propose a generator with the following parameters:

- **modulus** $2^{31} - 1$: the modulus should be the maximum prime number that can be represented in the target system.

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Although all modern computers have a 64-bit architecture, we considered a 32-bit one because the algorithm to find the right multiplier for a 64-bit modulus can be very slow. For this reason we have chosen $2^{31} - 1$ as our modulus.

- **multiplier 50812**: the multiplier should be *full-period modulus-compatible* with respect to the chosen modulus. The chosen modulus has 23093 of such multipliers. Among these there are also multipliers such 16807, widely used in the past, and 48271, that is currently the most widely adopted. We have chosen 50812 as our multiplier because we wanted to study a suitable multiplier that is different from the de-facto standard.
- **256 streams**: the original periodic random sequence can be partitioned in different disjoint periodic random subsequences, one for each stream. The number of streams should be no more than the number of required disjoint subsequences, because streams come with the cost of reducing the size of the sequence. We have chosen 256 streams, that is a lot more than the strictly required for our simulations, because it is a de-facto standard hence it is useful for comparisons between our evaluation and the one proposed in [4].
- **jump multiplier 29872**: the jump multiplier is used to partition the random sequence in disjoint subsequences, one for each stream, whose length is often called jump size. The jump multiplier should be modulus compatible with the chosen modulus. We have chosen 29872 as our jump multiplier because it is the value that maximizes the jump size.
- **initial seed 123456789**: the initial seed is the starting point of the finite sequence of generated values. Even if the initial seed does not impact the randomness degree of a generator in a single run (it only has to be changed in different replication of the same ensemble), we decide to indicate it here for completeness.

The randomness degree of such a generator has been assessed by the usage of *spectral test*, *test f extremes* and the *analysis of Kolomogorv-Smirnov*. The experimental results are reported in Section 4.

3 MODELING

We consider the environment sketched in Figure ??, that is characterized by:

- **workload**: mobile devices send to the system tasks that can be partitioned in two classes C_1 and C_2 .
- **system**: a two-tiers system, made of:
 - a remote Cloud server with virtually unlimited servants.
 - a Cloudlet with N servants, having the ability to off-load tasks to the Cloud, accordingly to a certain *off-loading policy* parametrized by a given *threshold*.

We assume that (i) the Cloudlet provides tasks with higher service rate than the Cloud, (ii) when a task is interrupted in the Cloudlet and it is sent to the Cloud, the restart process comes with a *setup time overhead*.

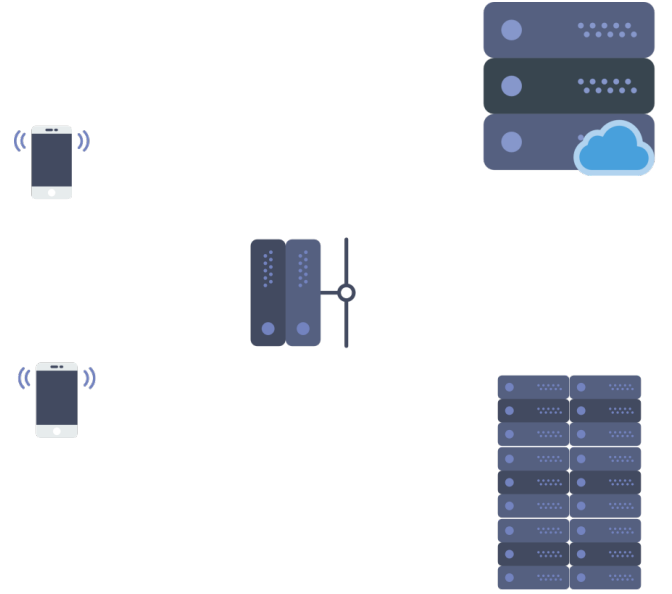


Figure 1: The system sketch.

Goals and Objectives. The main goals of the simulation are about system tuning. In particular, we propose to determine with a 95% level of confidence

- the response time as a function of the threshold S ,
- the throughput as a function of the threshold S ,
- the distribution of the response time when $S = N$ and
- the threshold of the off-loading policy that minimizes the response time.

Conceptual Model. The conceptual model is depicted in Figure??.

Specification Model. The state of the system is represented by the pair $(n_{clt,1}, n_{clt,2}, n_{cld,1}, n_{cld,2})$, where $n_{cld,i}$ is the number of tasks belonging to the i -th class within the Cloudlet and $n_{cld,i}$ is the number of tasks belonging to the i -th class within the Cloud. Tasks belonging to the first class, i.e. $t \in C_1$ arrive to the system with an exponential arrival process with rate λ_1 ; whilst tasks belonging to the second class, i.e. $t \in C_2$ arrive to the system with an exponential arrival process with rate λ_2 . The Cloudlet serves tasks belonging to the first class with exponentially distributed service time with rate $\mu_{cld,1}$; whilst the Cloudlet serves tasks belonging to the second class with exponentially distributed service time with rate $\mu_{cld,2}$. The Cloud serves tasks belonging to the first class with exponentially distributed service time with rate $\mu_{clt,1}$; whilst the Cloudlet serves tasks belonging to the second class with exponentially distributed service time with rate $\mu_{clt,2}$. We assume that (i) $\mu_{clt,i} > \mu_{cld,i} \forall i = 1, 2$ and (ii) the setup time T_{setup} is exponentially distributed with expected value $E[T_{setup}]$.

Computational Model. The proposed performance model has been implemented as a Python application. The simulation parameters can be configured with a simple YAML file that can be loaded by the simulation program. The full open source code is available at [5]

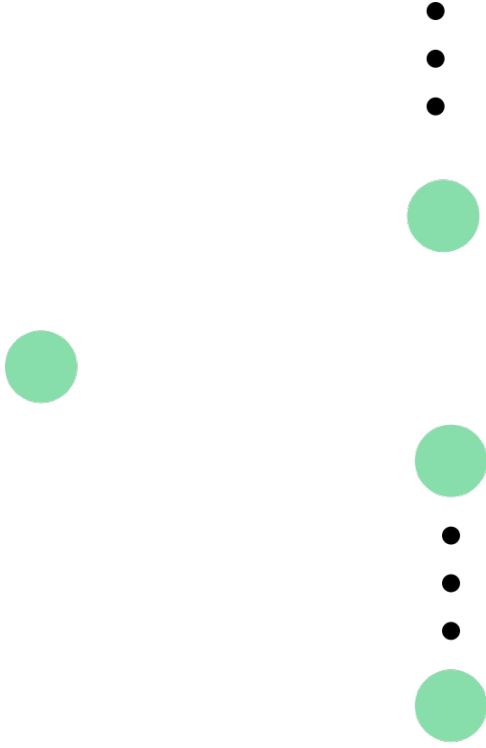


Figure 2: The conceptual model.

```

if task of class 1 then
  if  $n_{clt} = N$  then
    | send on the Cloud
  end
  if  $n_{clt} + n_{cld} < S$  then
    | accept
  end
  if  $n_{cld} > 0$  then
    | accept the task on the Cloudlet and send a class 2 task
    | on the Cloud
  else
    | accept the task on the Cloudlet
  end
end
if arrival of class 2 then
  if  $n_{clt} + n_{cld} \geq S$  then
    | send on the Cloud
  else
    | accept the task on the Cloudlet
  end
end

```

Algorithm 1: The dispatching policy.

and some representative configurations and outputs are presented in Section 5.

We adopted the next-event simulation paradigm, using (i) a custom multi-stream Lehmer generator to generate random events,

whose parameters have been described in Section 2 and whose evaluation will be presented in Section 4; and (ii) a priority-queue based calendar with the ability both to schedule and un-schedule events.

Verification. The model has been verified by

- **flow consistency check:** responsible to check flow trends, such as

$$n_{cld,i} = a_{cld,i} - c_{cld,i} - s_{cld,i} \quad (2)$$

$$n_{cld,i} = a_{cld,i} - c_{cld,i} + s_{cld,i} \quad (3)$$

$$s_{clt,i} = s_{cld,i} \quad (4)$$

where $n_{j,i}$ is the population of tasks belonging to i -th class in the j -th subsystem, $a_{j,i}$ is the number of tasks belonging to i -th class arrived to the j -th subsystem, $c_{j,i}$ is the number of tasks belonging to i -th class completed in the j -th subsystem, $s_{j,i}$ is the number of tasks belonging to i -th class switched from/to the j -th subsystem,

- **stationary check:** responsible to verify the model correctness in stationary conditions.

Validation. It is well-known that model development should includes a final validation step. Clearly, we cannot conduct this final step because we cannot compare the performance model with its real counterpart.

4 EVALUATION

In this Section, we present our experimental results. First, we show the results about the randomness of the adopted random number generator. Then, we show the results about the performance recorded by the simulation of the Cloud system.

The experiments have been conducted on an Amazon EC2 c3.8xlarge instance, which is really indicated for high performance science and engineering applications¹. The instance is equipped with 32 vCPU based on an Intel Xeon E5-2680 v2 (Ivy Bridge) processor, 30 GB of RAM and SSD with 900 IOPS. It runs Debian 8.3 (Jessie), Python 3.5.2, and the Python-ported version of the official Leemis library for discrete-event simulation, indicated in [4]. Our solution has been developed in Python, following the de-facto standard best-practices, stated in [1, 6].

4.1 Randomness

Let us now consider the results about the randomness of the adopted generator. The randomness has been assessed by the following tests:

- **Spectral Test:** this test is considered one of the most powerful tests to assess the quality of linear congruential generators [2]. It relies on the fact that the output of such generators form lines or hyperplanes when plotted on 2 or more dimensions. The less the distance between these lines or planes, the better the generator is. In fact, a smaller distance between lines or planes highlights a better uniform distribution. In Figure ?? we show the test results for generators $(16807, 2^{31} - 1)$, $(48271, 2^{31} - 1)$ and $(58012, 2^{31} - 1)$, respectively.

¹<https://aws.amazon.com/ec2/instance-types/>

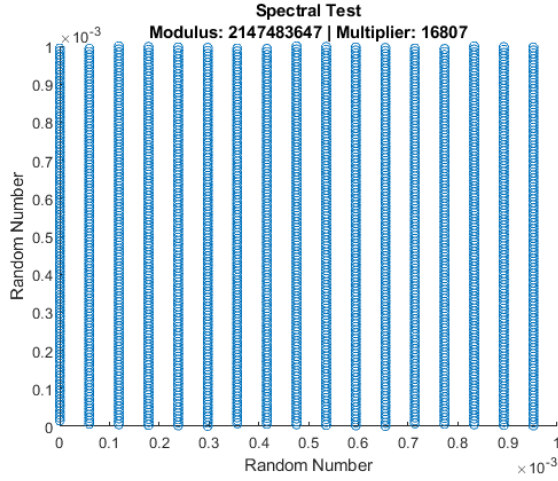


Figure 3: The Spectral Test to evaluate the randomness of the random number generator $(16807, 2^{31} - 1, 1)$ in the interval $(0, 10^{-3})$.

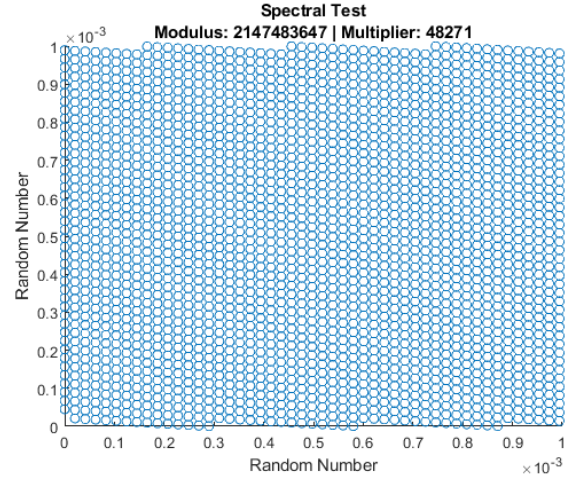


Figure 4: The Spectral Test to evaluate the randomness of the random number generator $(48271, 2^{31} - 1, 1)$ in the interval $(0, 10^{-3})$.

The results show that our generator $(58012, 2^{31} - 1)$ is much better than $(16807, 2^{31} - 1)$, which was a past de-facto standard, and really similar to $(48271, 2^{31} - 1)$, which is the current de-facto standard, according to [4].

- **Test of Extremes:** this test relies on the fact that if $U = U_0, \dots, U_{d-1}$ is an iid sequence of Uniform(0,1) random variables, then $\max(U)^d$ is also a Uniform(0,1). The test leverages this property to measures, for every stream, how much the generated random values differ from the theoretical uniform distribution.

The more the total number of fails is close to the expected value, i.e. *streams · confidence*, the better the generator is. In Figure ?? we show the test results for the proposed generator $(508012, 2^{31} - 1, 256)$ with sample size $n = 10000$, $k = 1000$ bins, sequence size $d = 5$ and 95% level of confidence. The proposed generator shows critical values $v_{min} = 913$ and $v_{max} = 1088$ and 14 total fails (7 lower fails and 7 upper fails), that is not far from the theoretical accepted number of fails, i.e. $256 \cdot 0.05 = 13$. The proposed generator successfully passed the test with a 94.531% level of confidence.

- **Kolmogorov-Smirnov Analysis:** the test measures, at a certain confidence level, the biggest vertical distance between the theoretical cumulative distribution function and the empirical cumulative distribution function. The more the recorded distance d is less than the critical value d^* for the considered level of confidence, the better the generator is. As the Kolmogorov-Smirnov analysis relies on pre-calculated randomness statistics, we have chosen to take into account the statistics obtained by the previous text of extremes. In Figure ?? we show the test results for the proposed generator $(508012, 2^{31} - 1, 256)$ with a 95% level of confidence. The proposed generator successfully passed the test, as $d = 0.041 < 0.081 = d^*$.

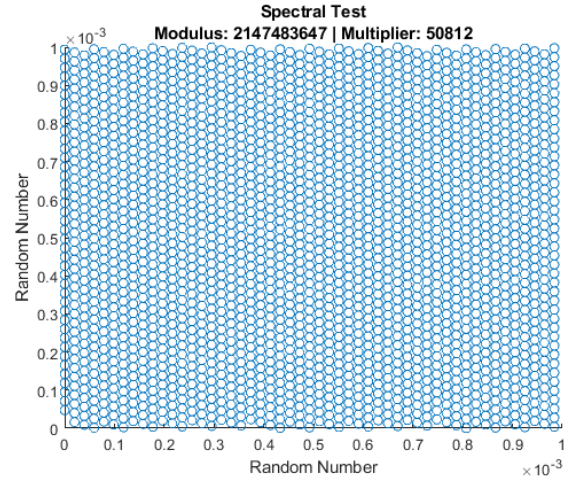


Figure 5: The Spectral Test to evaluate the randomness of the random number generator $(50812, 2^{31} - 1, 1)$ in the interval $(0, 10^{-3})$.

4.2 Performance Analysis

Let us now consider the results about the performance recorded by the simulation of the system. In all the experiments we consider the following parameters:

- **arrivals:** exponential with rate $\lambda_1 = 3.25task/s$ and $\lambda_2 = 6.25task/s$.
- **services:** exponential with rate $\mu_{clt,1} = 0.45task/s$, $\mu_{clt,2} = 0.30task/s$, $\mu_{cld,1} = 0.25task/s$ and $\mu_{cld,2} = 0.22task/s$.
- **setup:** exponential with mean $E[T_{setup}] = 0.8s$.

arrival rates, exponential service rates and exponential setup time

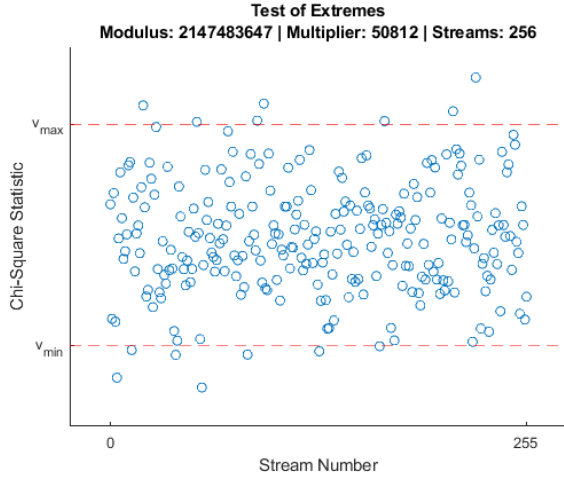


Figure 6: The Test of Extremes with $d = 5$ to evaluate the randomness of the random number generator ($50812, 2^{31} - 1, 256$).

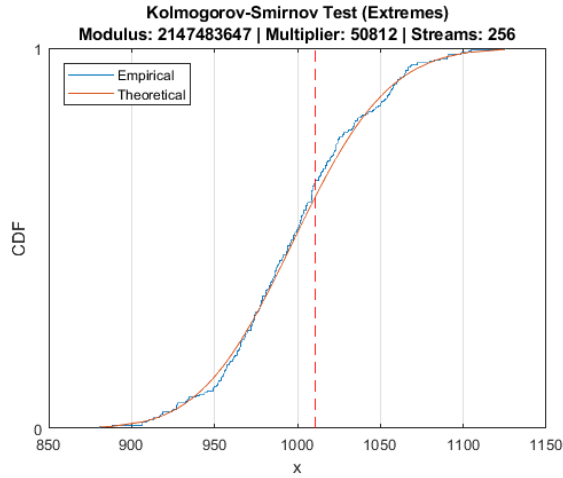


Figure 7: The Kolmogorov-Smirnov Analysis (leveraging the Test of Extremes with $d = 5$) to evaluate the randomness of the random number generator ($50812, 2^{31} - 1, 256$) with 0.95 confidence level.



Figure 8: Response Time Analysis, as a function of N .



Figure 9: Throughput Analysis, as a function of N .



Figure 10: The response time distribution with $S = N$.

TEST OF EXTREMES

Generator

```

Class ..... MarcianiMultiStream
Streams ..... 2 5 6
Modulus ..... 2 1 4 7 4 8 3 6 4 7
Multiplier ..... 5 0 8 1 2
Seed ..... 1 2 3 4 5 6 7 8 9

```

Test Parameters

```

Sample Size ..... 1 0 0 0
Bins ..... 1 0 0
Confidence ..... 9 5 . 0
D ..... 5

```

Critical Bounds

```

Lower Bound ..... 9 1 3 . 3 0 0 9 9 8 3 0 9 0 6 4 4
Upper Bound ..... 1 0 8 8 . 4 8 7 0 6 7 5 3 3 8 2 6 1

```

Error

```

Theoretical ..... 1 3 (5.078 %)
Empirical ..... 1 4 (5.469 %)
Empirical Lower Bound ..... 7 (2.734 %)
Empirical Upper Bound ..... 7 (2.734 %)

```

Result

```

Suggested Confidence ..... 9 4 . 5 3 1
Success ..... False

```

Figure 11: A sample output of the Test of Extremes.

5 USAGE

In this Section we show how to configure and run experiments and some sample outputs to provide a better idea of what has been created.

The test of extremes for a custom random number generator produces the output shown in Figure ?? and can be executed with default configuration by running the following script

```
python experiments.py extremes
```

The test of Kolmogorov-Smirnov for a custom random number generator produces the output shown in Figure ?? and can be executed with default configuration by running the following script

```
python experiments.py kolmogorov-smirnov
```



```

=====
TEST OF KOLMOGOROV-SMIRNOV
=====

Generator
Class ..... MarcianiMultiStream
Streams ..... 2 5 6
Modulus ..... 2 1 4 7 4 8 3 6 4 7
Multiplier ..... 5 0 8 1 2
Seed ..... 1 2 3 4 5 6 7 8 9

Test Parameters
Chi-Square Test ..... extremes
Sample Size ..... 1 0 0 0 0
Bins ..... 1 0 0 0
Confidence ..... 9 5 . 0
D ..... 5

KS
KS Statistic ..... 0 . 0 4 1
KS Point X ..... 1 0 1 0 . 6
KS Critical Distance ..... 0 . 0 8 4

Result
Success ..... True

```

Figure 12: A sample output of the Test of Kolmogorov-Smirnov.

The simulation is configured providing a configuration YAML file as the one shown in Figure ??, produces the output shown in Figure ?? and can be executed with default configuration by running the following script

```
python experiments.py simulation
```

6 CONCLUSIONS

In this work we propose a next-event simulation model for a two-layer Cloud system, leveraging a custom multi-stream Lehmer pseudo-random number generator.

Although experimental results are pretty satisfactory, the proposed solutions could certainly be improved and be subjected to a more in-depth analysis. From an implementation point of view, the proposed solution should be ported from Python to C and leverage multi-threading to achieve better performances, e.g. to speed-up the algorithms to find suitable multipliers for modulus in 64-bit architectures and make the simulation faster. From an analysis point of view, the proposed random number generator should be tested more extensively, e.g. taking into account more tests of randomness, and a generator with a 64-bit modulus and less number of streams should be developed. Finally, the simulation model should be extended to take into account more performance metrics, such as utilization, to study the influence of different server selection

```

general:
  t_stop: 3600
  replications: 1000
  confidence: 0.95
  random:
    generator: "MarcianiMultiStream"
    seed: 123456789

tasks:
  arrival_rate_1: 3.25
  arrival_rate_2: 6.25

system:
  cloudlet:
    n_servers: 20
    service_rate_1: 0.45
    service_rate_2: 0.30
    threshold: 20
    server_selection: "ORDER"

  cloud:
    service_rate_1: 0.25
    service_rate_2: 0.22
    t_setup_mean: 0.8

```

Figure 13: A sample configuration for a simulation experiment.

policies, e.g. equity-selection, and to achieve more performance evaluation goals, such as forecasting.

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- [6] Kenneth Reitz and Tanya Schlusser. 2016. *The Hitchhiker's Guide to Python: Best Practices for Development*. O'Reilly Media. <http://amzn.to/2bYCvBD>

```

=====
SIMULATION
=====

general
simulation_class ..... SimpleCloudSimulation
t_stop ..... 1 0 0
replications ..... 1 0 0
confidence ..... 0.95

tasks
arrival_rate_1 ..... 3.25
arrival_rate_2 ..... 6.25
n_generated_1 ..... 3 2 5 3
n_generated_2 ..... 3 2 4 4

system
n_arrival_1 ..... 3 2 5 3
n_arrival_2 ..... 3 2 4 4
n_served_1 ..... 3 2 5 3
n_served_2 ..... 3 2 4 4
throughput ..... 6.42
response_time (mean) ..... 2.776
response_time (stddev) ..... 2.844
utilization ..... 0.997

system/cloudlet
n_servers ..... 2 0
service_rate_1 ..... 0.45
service_rate_2 ..... 0.3
threshold ..... 2 0
server_selection_rule ..... ORDER
n_arrival_1 ..... 3 2 5 3
n_arrival_2 ..... 2 9 6 5
n_served_1 ..... 3 2 5 3
n_served_2 ..... 2 6 5 8
n_removed_2 ..... 3 0 7
t_service_1 ..... 7 2 0 6.935
t_service_2 ..... 7 9 0 2.827
t_wasted_2 ..... 7 4 0.36

system/cloud
service_rate_1 ..... 0.25
service_rate_2 ..... 0.22
setup_mean ..... 0.8
n_arrival_1 ..... 0
n_arrival_2 ..... 5 8 6
n_served_1 ..... 0
n_served_2 ..... 5 8 6
n_restarted_2 ..... 3 0 7
t_service_1 ..... 0.0
t_service_2 ..... 3 0 1 6.008

```

Figure 14: A sample simulation output.