

PRODUCTION SYSTEM

Applications of AI/ML in operations and
supply chain management

SimPy discrete-event simulation framework

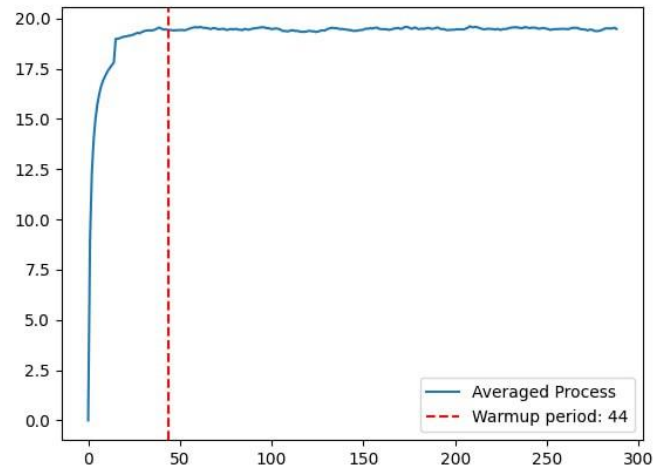
PUSH POLICY

Immediate placing of jobs along the machine chain

PUSH POLICY - Summary

Number and duration of simulations:

```
welch:
  simulations_number: 200
  until: 9125 # 25 years
```



```
push_system:
  stat_simulations_number: 800
  stat_simulation_until: 9125 # 25 years
```

Sampling:

```
throughput_sampling: True
throughput_timestep: 30 # one month

wip_sampling: True
wip_timestep: 1 # one day
```

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.48	0.08	0.02	19.46, 19.50	0.08%

Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	5.87	1.31	0.07	5.80, 5.94	1.13%
Machine 2	9.78	3.00	0.10	9.68, 9.88	1.03%
Machine 3	18.86	18.49	0.25	18.61, 19.11	1.33%
Machine 4	19.73	11.99	0.20	19.53, 19.93	1.02%
Machine 5	23.17	14.30	0.22	22.95, 23.39	0.95%
Machine 6	47.57	252.43	0.93	46.64, 48.49	1.94%

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	124.97	710.41	1.55	123.42, 126.52	1.24%

Min reward: -1425.4734743322392, Max reward: 799.6151988040212

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Reward	5.01	319.82	1.04	3.97, 6.05	20.78%

REINFORCEMENT LEARNING

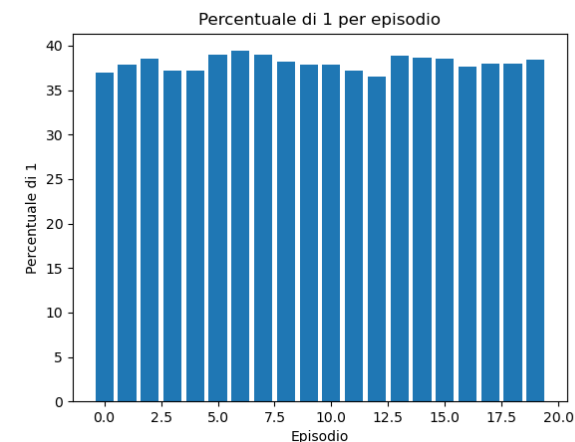
stable_baseline3 Reliable Reinforcement Learning Implementations

RL algorithms:

- **A2C**
- **PPO**
- **DQN**

A2C - Summary

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	17.95	0.23	0.19	17.77, 18.14	1.04%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	2.24	0.15	0.15	2.09, 2.40	6.78%
Machine 2	3.85	0.41	0.25	3.60, 4.10	6.46%
Machine 3	6.17	0.60	0.30	5.86, 6.47	4.88%
Machine 4	7.36	0.62	0.30	7.06, 7.67	4.13%
Machine 5	8.94	0.57	0.29	8.65, 9.23	3.26%
Machine 6	13.89	2.45	0.61	13.28, 14.49	4.36%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	42.46	14.78	1.49	40.97, 43.94	3.50%



```
time_step_length: 0.65

time_step_count: 8000

episode_count: 20
episode_welch_count: 5

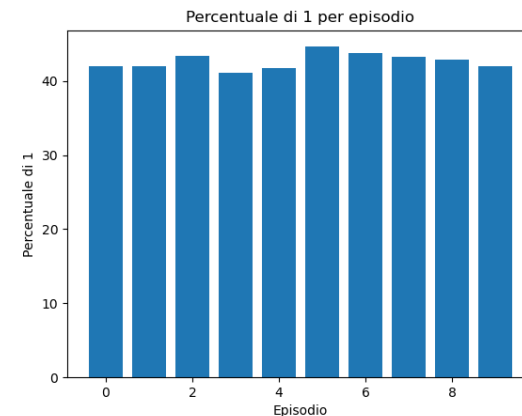
episode_length: 9125  # 25 years

learning_total_timesteps: 36500
```

```
reward:
reward_sampling: True
reward_time_step: 1
delivery_half_window: 7
daily_penalty: 5
award_delivery: 125
wip_penalty: 15  # if a queue grows, the reward is reduced
wip_award: 2  # 0.35
avoid_empty_queue_penalty: 125
job_late_penalty: 25
```

A2C - Summary

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.09	0.29	0.31	18.77, 19.40	1.65%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	3.73	0.55	0.43	3.30, 4.16	11.54%
Machine 2	6.62	2.27	0.87	5.75, 7.50	13.18%
Machine 3	11.89	7.82	1.62	10.27, 13.52	13.63%
Machine 4	13.24	6.04	1.43	11.82, 14.67	10.76%
Machine 5	15.85	8.88	1.73	14.12, 17.57	10.90%
Machine 6	26.46	37.25	3.54	22.93, 30.00	13.37%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	77.80	220.65	8.61	69.19, 86.41	11.07%



```
time_step_length: 0.65
time_step_count: 8000
episode_count: 10
episode_welch_count: 5
episode_length: 9125 # 25 years
learning_total_timesteps: 36500
```

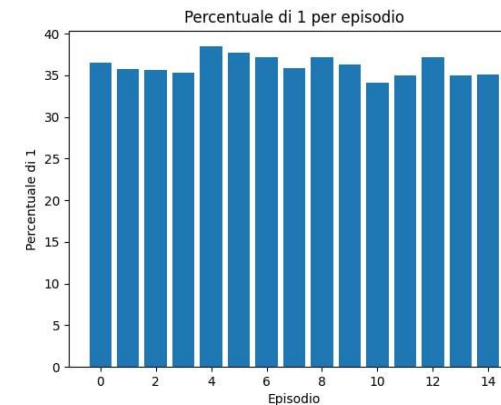
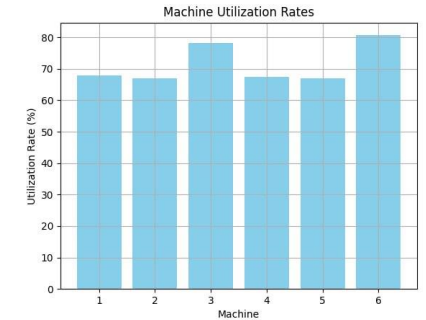
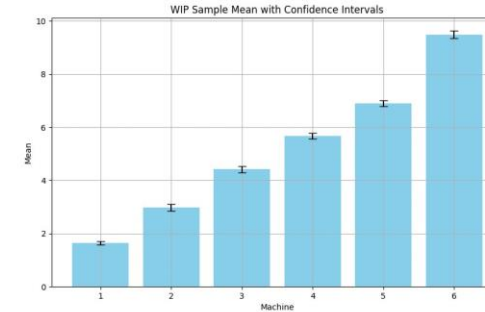
```
reward:
  reward_sampling: True
  reward_time_step: 1
  delivery_half_window: 7
  daily_penalty: 5
  award_delivery: 125
  wip_penalty: 15 # if a queue grows, the reward is reduced
  wip_award: 2 # 0.35
  avoid_empty_queue_penalty: 100
  job_late_penalty: 25
```

DQN - Summary

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	17.06	0.34	0.27	16.79, 17.32	1.55%

Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	1.64	0.02	0.07	1.57, 1.71	4.24%
Machine 2	2.97	0.09	0.14	2.84, 3.11	4.57%
Machine 3	4.42	0.07	0.12	4.30, 4.54	2.72%
Machine 4	5.68	0.06	0.11	5.57, 5.79	1.94%
Machine 5	6.90	0.06	0.11	6.79, 7.02	1.63%
Machine 6	9.49	0.10	0.14	9.35, 9.64	1.52%

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	31.10	0.48	0.32	30.79, 31.42	1.01%



```
time_step_length: 0.65
time_step_count: 8000
episode_count: 15
episode_welch_count: 5
episode_length: 9125 # 25 years
learning_total_timesteps: 40000
```

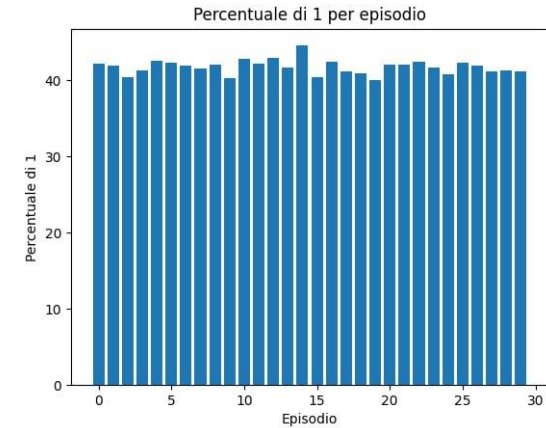
```
reward:
  reward_sampling: True
  reward_time_step: 1
  delivery_half_window: 7
  daily_penalty: 5
  award_delivery: 125
  wip_penalty: 25 # if a queue grows, the reward is reduced
  wip_award: 15
  avoid_empty_queue_penalty: 100
  job_late_penalty: 0
```


DQN - Summary

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.51	0.26	0.16	19.35, 19.67	0.81%

Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	4.67	3.94	0.62	4.05, 5.28	13.18%
Machine 2	7.84	5.78	0.75	7.10, 8.59	9.51%
Machine 3	16.92	52.98	2.26	14.66, 19.18	13.34%
Machine 4	16.66	31.95	1.75	14.91, 18.41	10.53%
Machine 5	19.81	35.11	1.84	17.97, 21.65	9.28%
Machine 6	38.43	225.52	4.66	33.77, 43.09	12.12%

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	104.33	1220.28	10.84	93.49, 115.17	10.39%

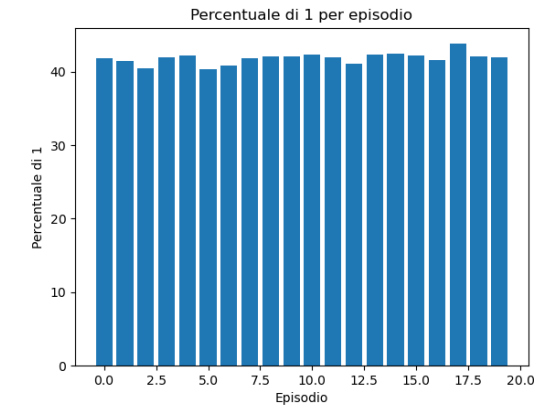


```
time_step_length: 0.65
time_step_count: 8000
episode_count: 30
episode_welch_count: 5
episode_length: 9125 # 25 years
learning_total_timesteps: 40000
```

```
reward:
  reward_sampling: True
  reward_time_step: 1
  delivery_half_window: 7
  daily_penalty: 5
  award_delivery: 115
  wip_penalty: 15 # if a queue grows, the reward is reduced
  wip_award: 3
  avoid_empty_queue_penalty: 100
  job_late_penalty: 25
```


PPO - Summary

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.44	0.23	0.19	19.25, 19.63	0.96%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	4.33	2.23	0.58	3.75, 4.91	13.33%
Machine 2	7.32	4.13	0.79	6.53, 8.10	10.74%
Machine 3	14.09	21.37	1.79	12.31, 15.88	12.68%
Machine 4	15.41	20.24	1.74	13.67, 17.15	11.28%
Machine 5	18.12	21.18	1.78	16.34, 19.90	9.82%
Machine 6	31.77	118.42	4.21	27.57, 35.98	13.24%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	91.05	654.24	9.89	81.16, 100.94	10.86%



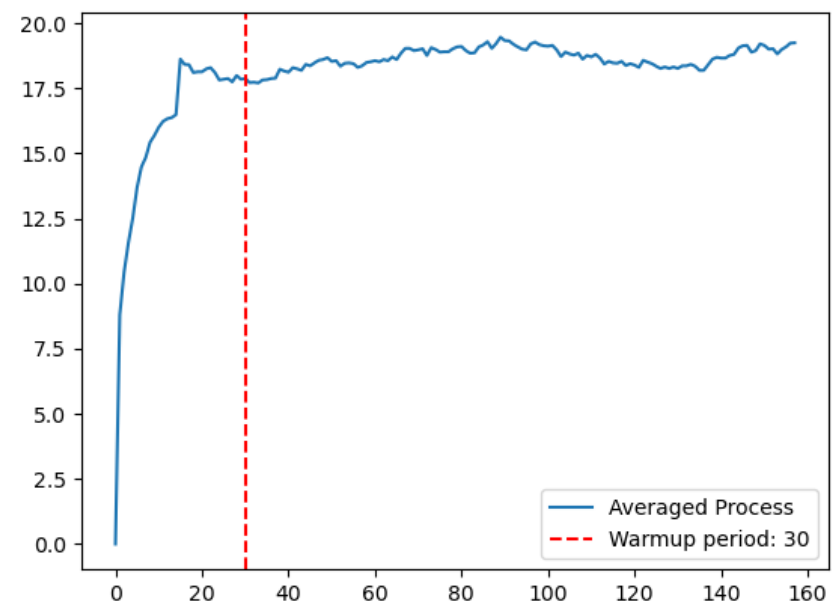
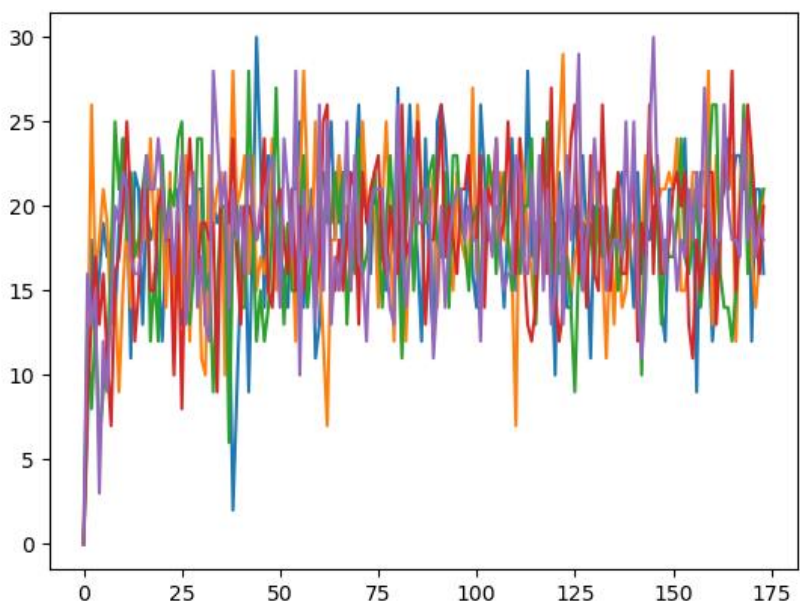
```
time_step_length: 0.65
time_step_count: 8000
episode_count: 20
episode_welch_count: 5
episode_length: 9125 # 25 years
learning_total_timesteps: 40000
```

```
reward:
  reward_sampling: True
  reward_time_step: 1
  delivery_half_window: 7
  daily_penalty: 5
  award_delivery: 125
  wip_penalty: 10 # if a queue grows, the reward is reduced
  wip_award: 1 # 0.35
  avoid_empty_queue_penalty: 125
  job_late_penalty: 25
```

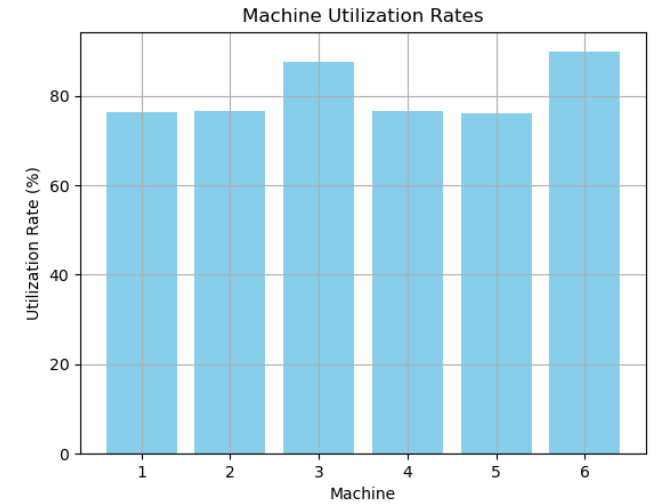
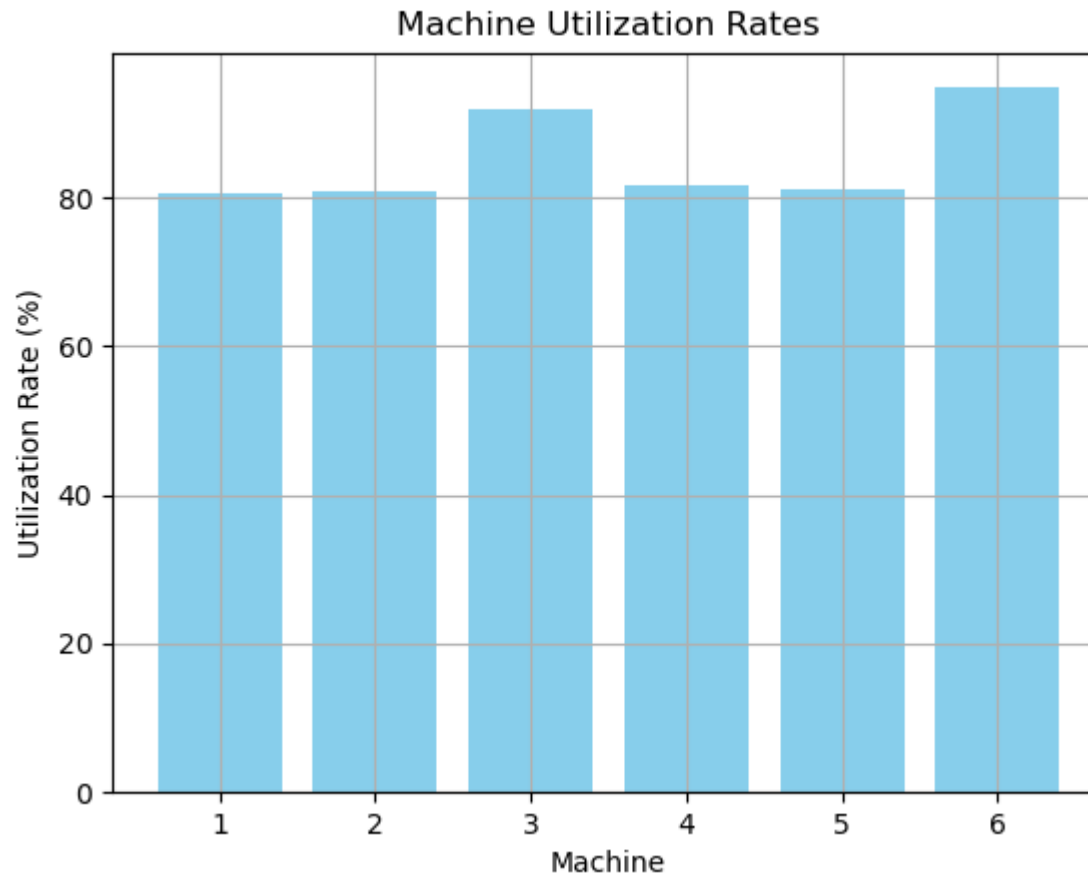
GENERAL DATA

Data common and similar to all cases.

Welch Analysis



Utilization rate

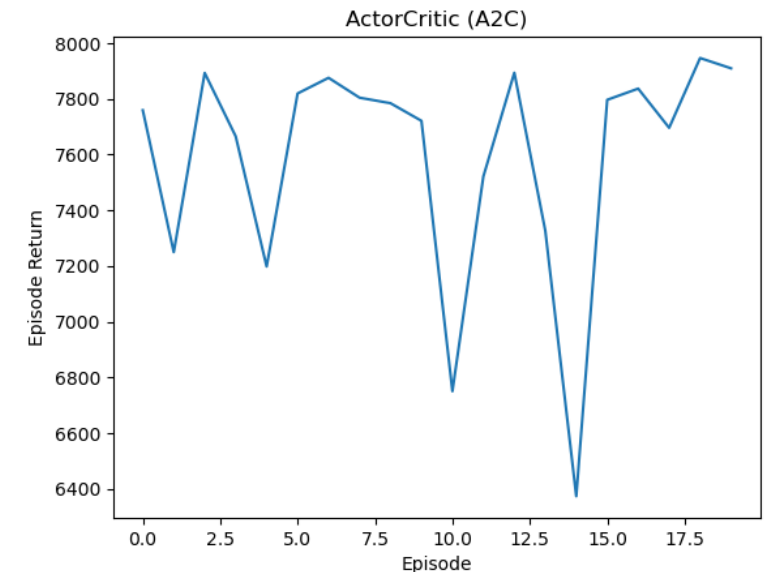
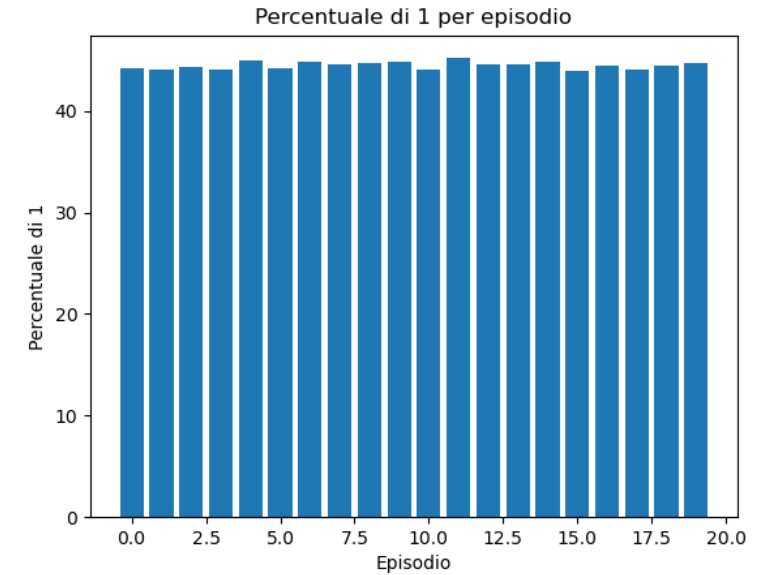


Simulations with different gamma

Before gamma was 0,99

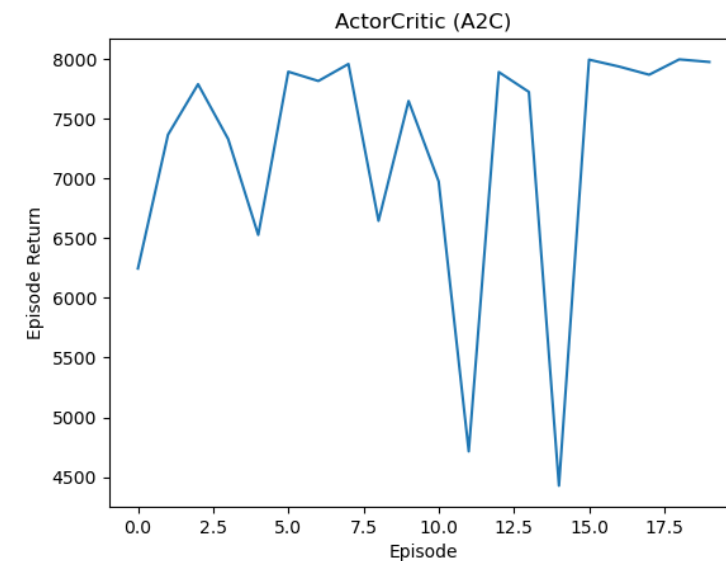
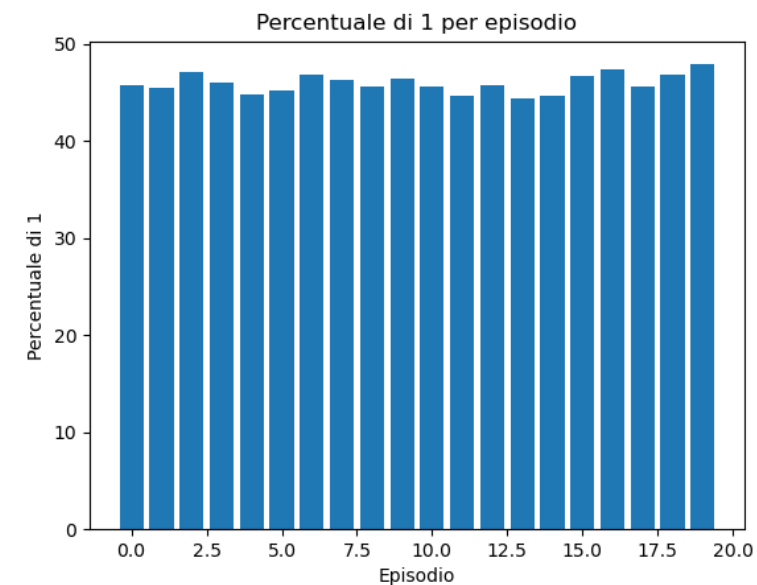
A2C – gamma 0,5

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.54	0.08	0.11	19.43, 19.65	0.56%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	4.78	0.43	0.25	4.52, 5.03	5.28%
Machine 2	8.40	2.03	0.55	7.85, 8.95	6.55%
Machine 3	15.93	10.61	1.26	14.67, 17.19	7.91%
Machine 4	17.13	7.66	1.07	16.06, 18.20	6.25%
Machine 5	20.59	7.69	1.07	19.51, 21.66	5.21%
Machine 6	42.30	107.81	4.01	38.28, 46.31	9.49%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	109.12	289.79	6.58	102.54, 115.70	6.03%



A2C – gamma 0,15

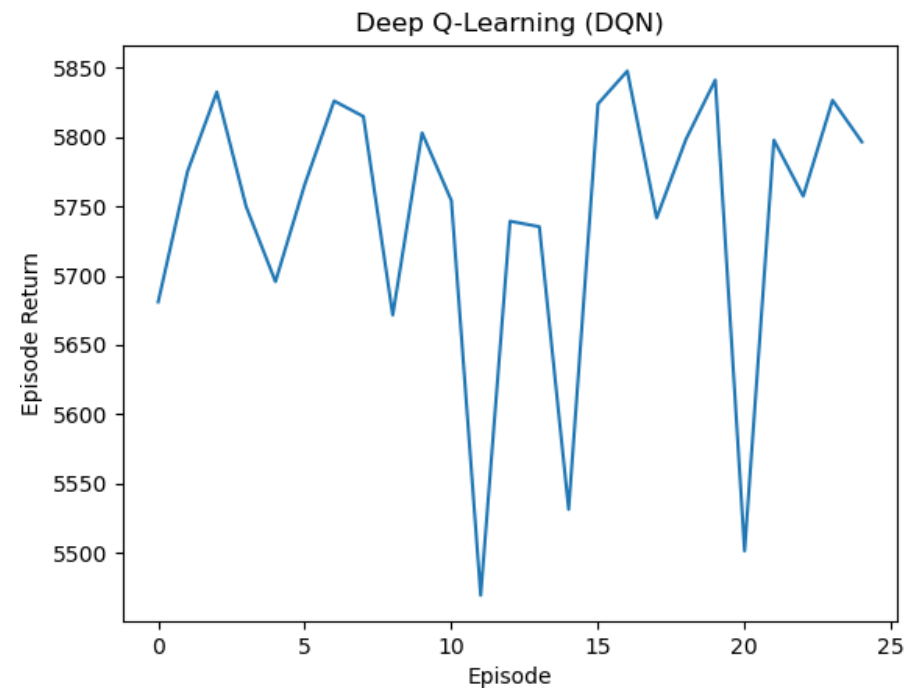
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.53	0.08	0.11	19.42, 19.65	0.57%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	4.37	0.30	0.21	4.16, 4.58	4.88%
Machine 2	7.70	1.57	0.48	7.21, 8.18	6.30%
Machine 3	14.35	3.87	0.76	13.59, 15.11	5.30%
Machine 4	15.65	3.44	0.72	14.93, 16.36	4.58%
Machine 5	19.01	4.37	0.81	18.20, 19.82	4.25%
Machine 6	36.80	34.55	2.27	34.52, 39.07	6.18%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	97.86	117.32	4.19	93.67, 102.05	4.28%



DQN – gamma 0,99

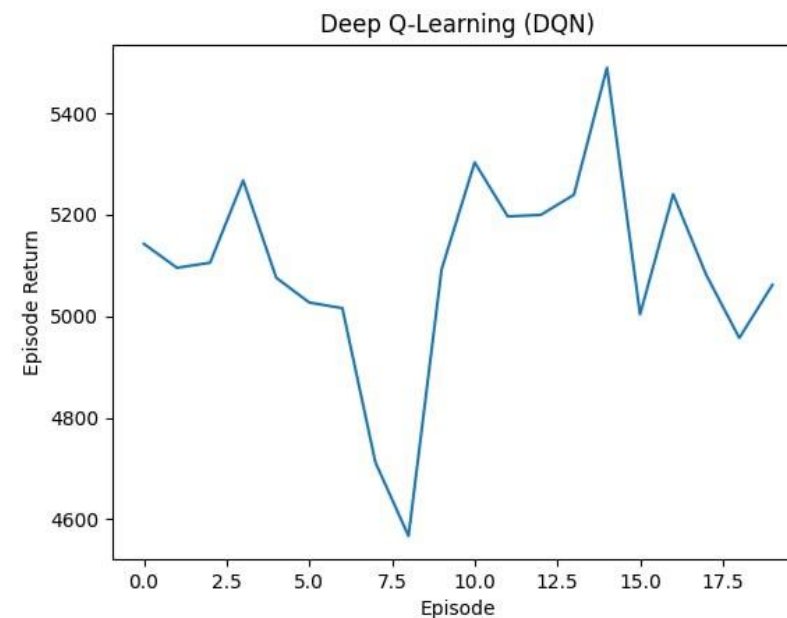
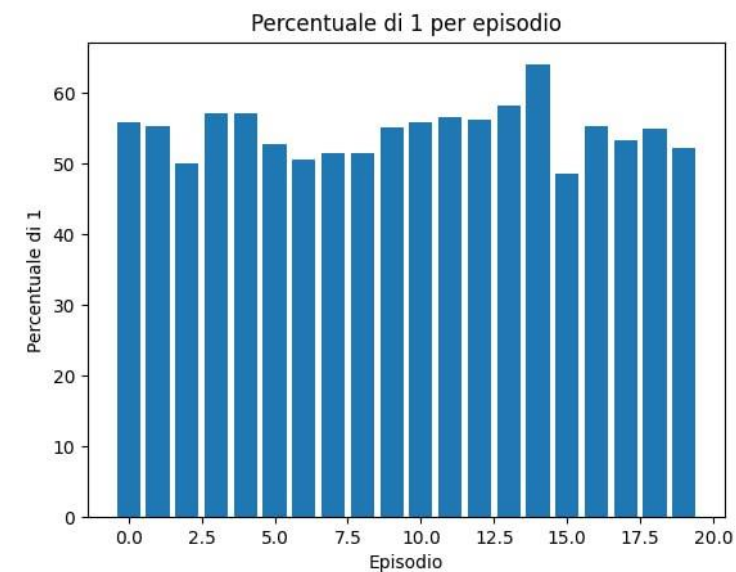
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.51	0.09	0.10	19.41, 19.62	0.53%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	5.52	3.22	0.61	4.90, 6.13	11.12%
Machine 2	9.39	8.24	0.98	8.41, 10.38	10.46%
Machine 3	18.71	23.94	1.67	17.03, 20.38	8.95%
Machine 4	19.37	17.67	1.44	17.93, 20.81	7.43%
Machine 5	23.20	25.70	1.73	21.47, 24.94	7.48%
Machine 6	47.08	220.67	5.08	42.00, 52.17	10.80%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	123.27	908.07	10.31	112.96, 133.59	8.36%

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Reward	-51.48	118.80	3.73	-55.20, -47.75	-7.25%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Action 1	0.93	0.00	0.01	0.92, 0.94	1.15%



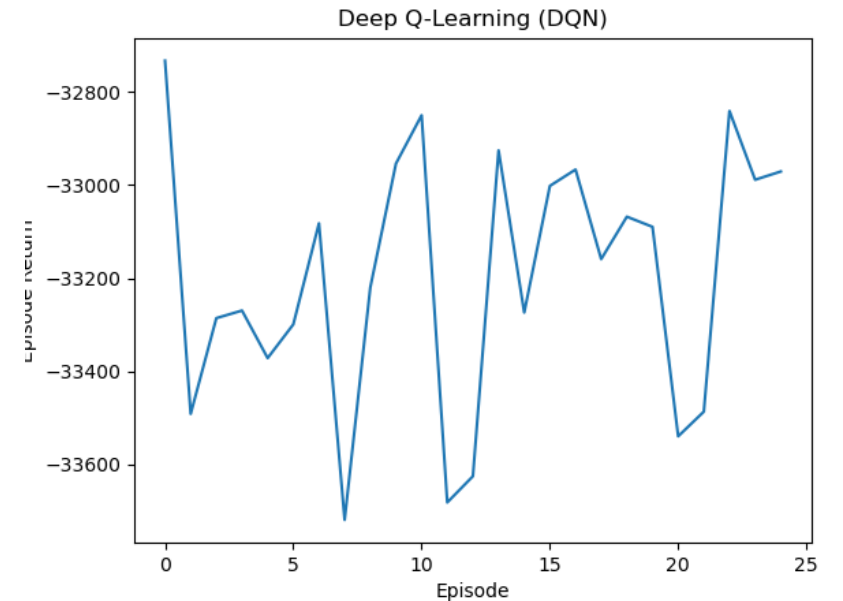
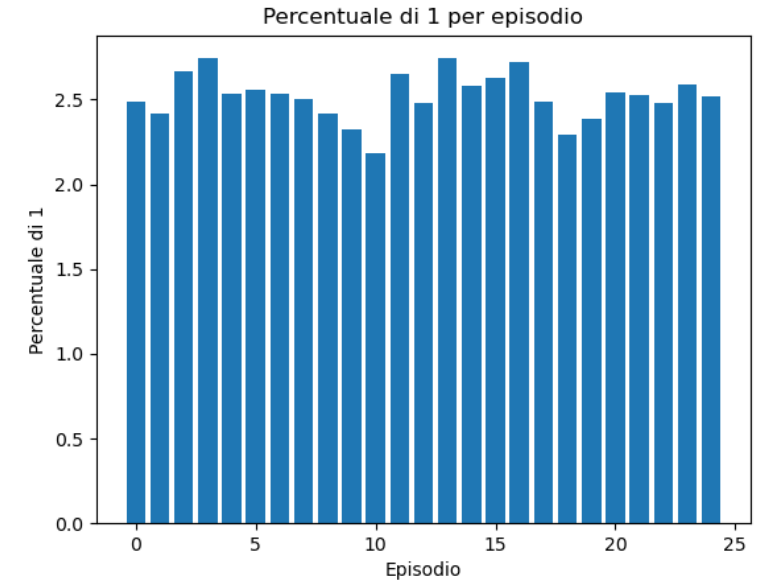
DQN – gamma 0,5

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.55	0.09	0.11	19.43, 19.66	0.58%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	18.26	8.56	1.13	17.12, 19.39	6.20%
Machine 2	23.03	14.33	1.46	21.56, 24.49	6.36%
Machine 3	36.27	36.84	2.35	33.93, 38.62	6.47%
Machine 4	37.93	27.57	2.03	35.90, 39.96	5.35%
Machine 5	42.24	28.51	2.06	40.18, 44.31	4.89%
Machine 6	68.05	179.74	5.18	62.86, 73.23	7.62%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	225.78	881.85	11.48	214.30, 237.26	5.09%



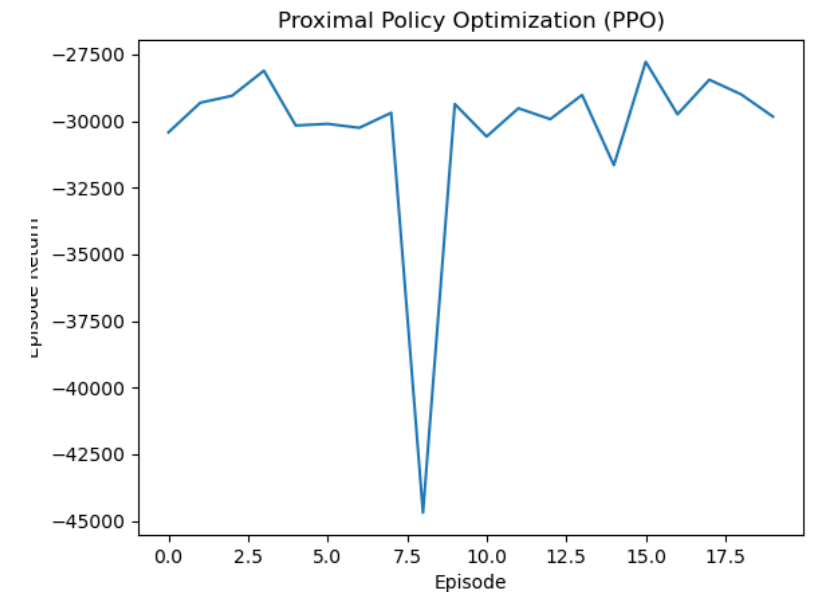
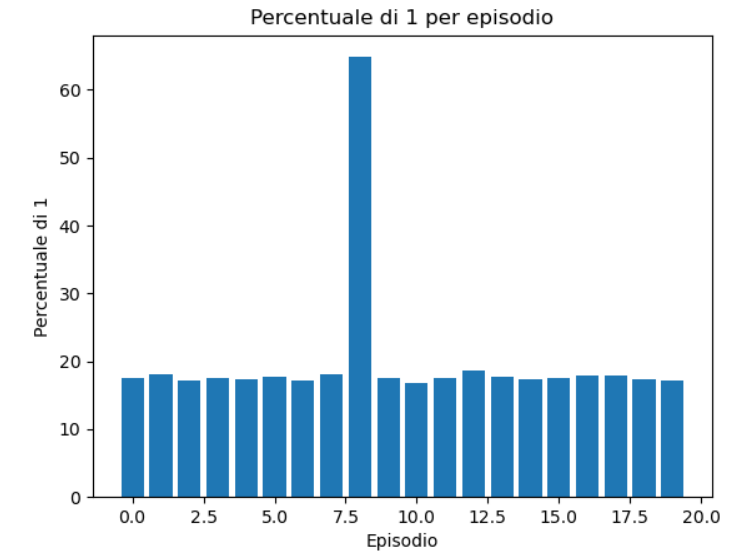
DQN – gamma 0,1

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	1.17	0.00	0.02	1.15, 1.19	1.85%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	0.00	0.00	0.00	0.00, 0.01	20.80%
Machine 2	0.01	0.00	0.00	0.01, 0.01	18.93%
Machine 3	0.01	0.00	0.00	0.01, 0.01	13.52%
Machine 4	0.01	0.00	0.00	0.01, 0.01	16.08%
Machine 5	0.01	0.00	0.00	0.01, 0.02	17.76%
Machine 6	0.02	0.00	0.00	0.02, 0.02	15.42%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	0.07	0.00	0.01	0.06, 0.07	11.90%



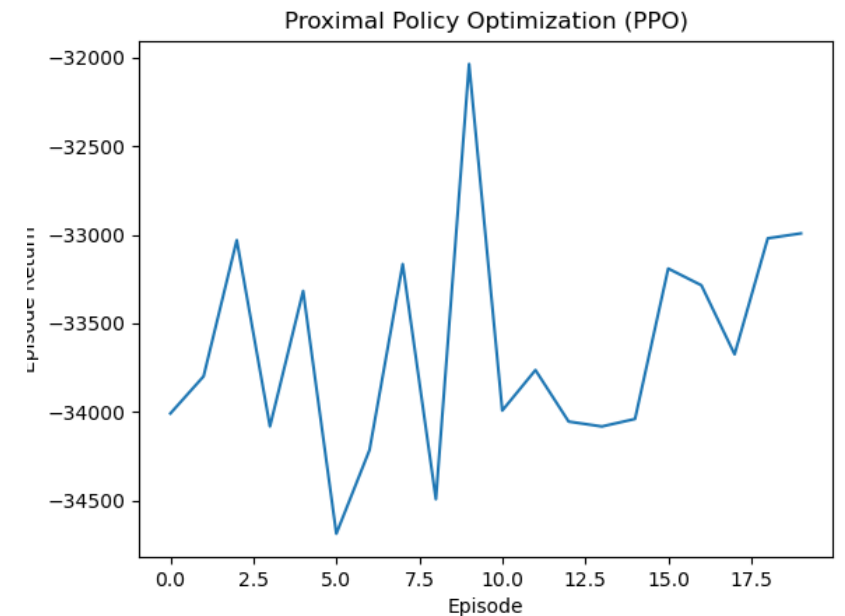
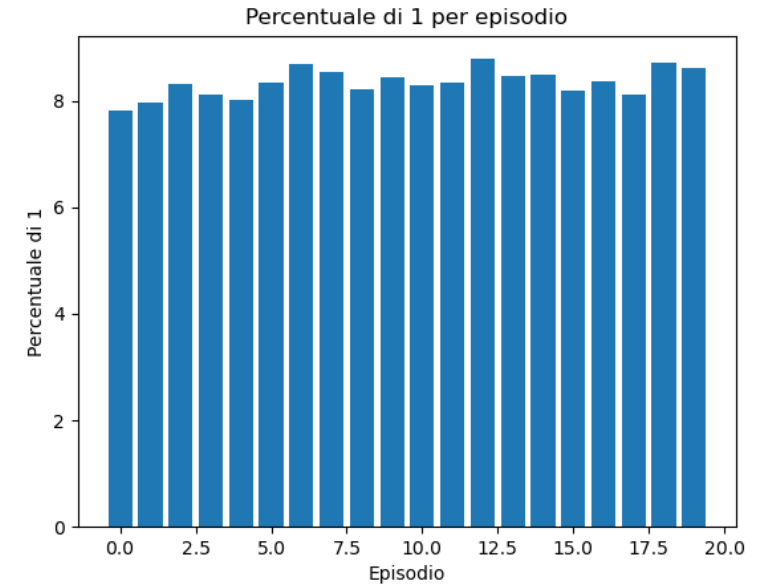
PPO – gamma 0,5

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	8.56	3.77	0.75	7.81, 9.31	8.78%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	15.30	4461.05	25.82	-10.52, 41.13	168.78%
Machine 2	16.02	4735.10	26.61	-10.58, 42.63	166.05%
Machine 3	30.83	18150.60	52.09	-21.26, 82.92	168.97%
Machine 4	27.84	14380.16	46.37	-18.52, 74.21	166.54%
Machine 5	28.05	14336.11	46.29	-18.25, 74.34	165.07%
Machine 6	38.10	26601.30	63.06	-24.96, 101.16	165.53%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	156.14	453032.65	260.24	-104.11, 416.38	166.68%



PPO – gamma 0,15

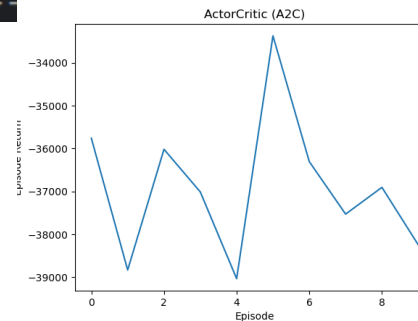
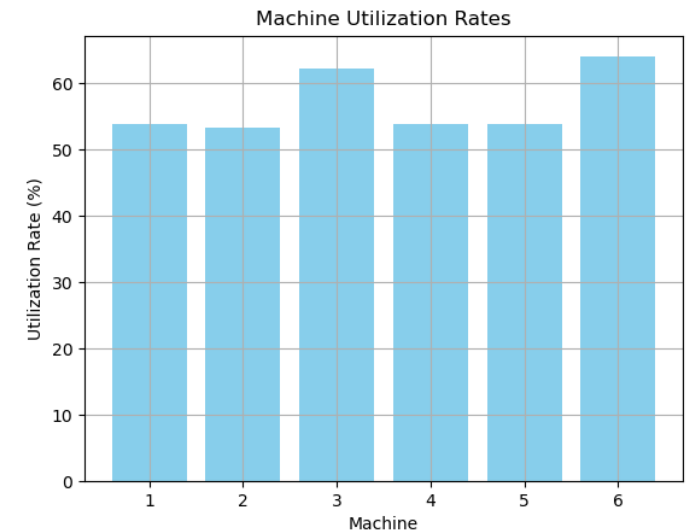
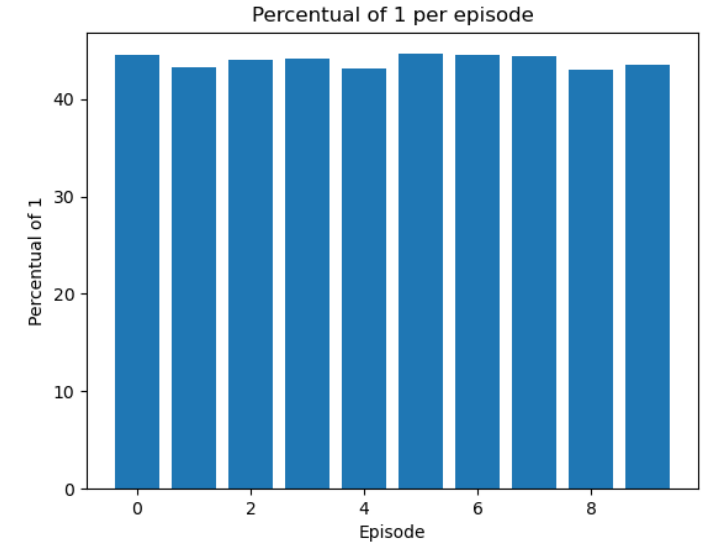
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	3.86	0.02	0.05	3.81, 3.91	1.34%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	0.05	0.00	0.01	0.04, 0.05	13.16%
Machine 2	0.09	0.00	0.01	0.08, 0.09	10.39%
Machine 3	0.09	0.00	0.00	0.09, 0.10	5.13%
Machine 4	0.15	0.00	0.02	0.13, 0.16	11.71%
Machine 5	0.18	0.00	0.02	0.16, 0.20	9.86%
Machine 6	0.24	0.00	0.02	0.22, 0.27	9.56%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	0.79	0.03	0.07	0.72, 0.86	8.48%



Simulations with different
time_step_length

A2C – time_step_length 1,0

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	13.19	0.03	0.11	13.08, 13.30	0.82%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	0.89	0.01	0.06	0.82, 0.95	7.29%
Machine 2	1.50	0.03	0.11	1.40, 1.61	7.18%
Machine 3	2.07	0.04	0.11	1.96, 2.19	5.50%
Machine 4	2.61	0.10	0.18	2.43, 2.79	6.88%
Machine 5	3.33	0.16	0.23	3.10, 3.56	6.99%
Machine 6	4.76	0.26	0.30	4.46, 5.05	6.22%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	15.17	2.60	0.93	14.23, 16.10	6.16%

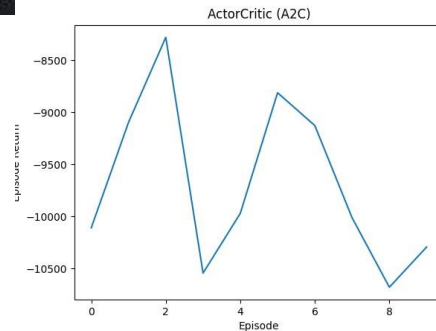
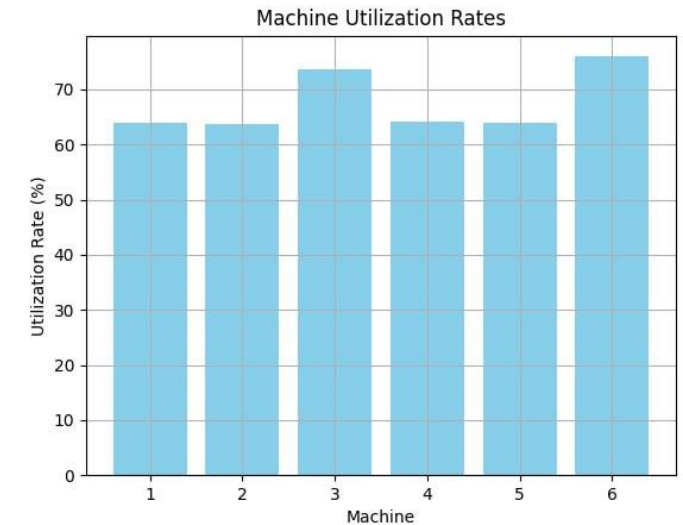
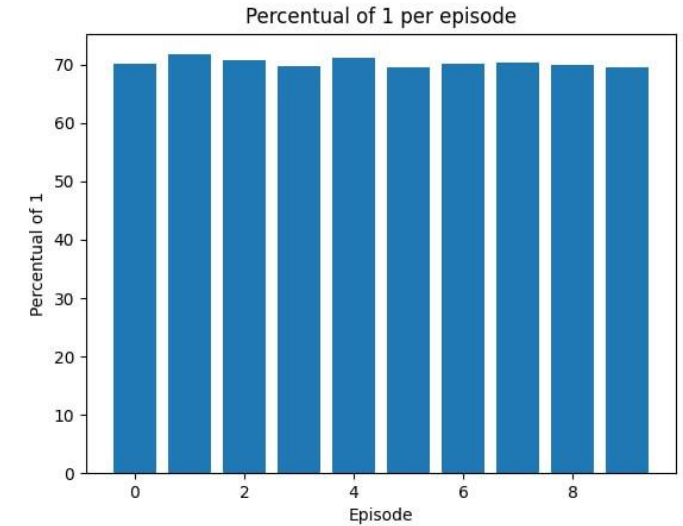


A2C – time_step_length 1,5

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	15.67	0.02	0.09	15.58, 15.76	0.58%

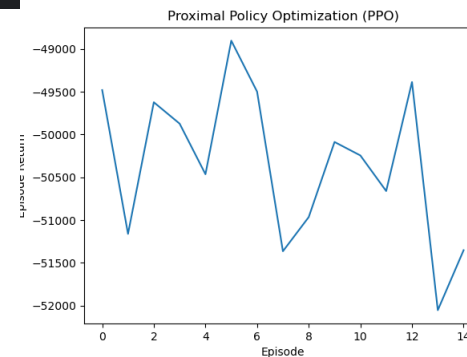
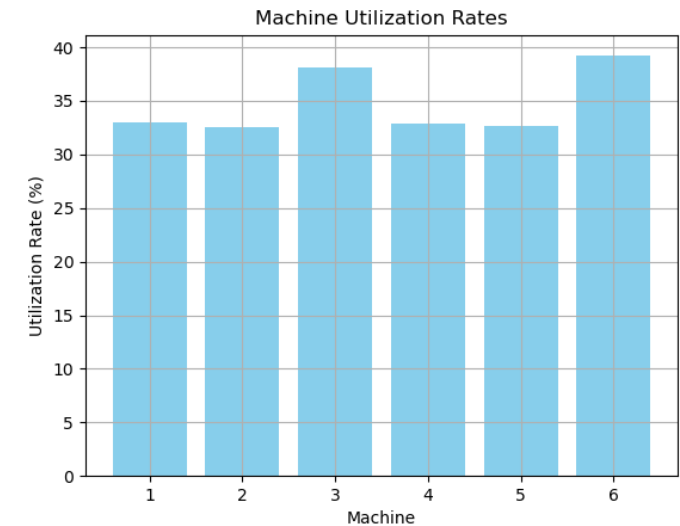
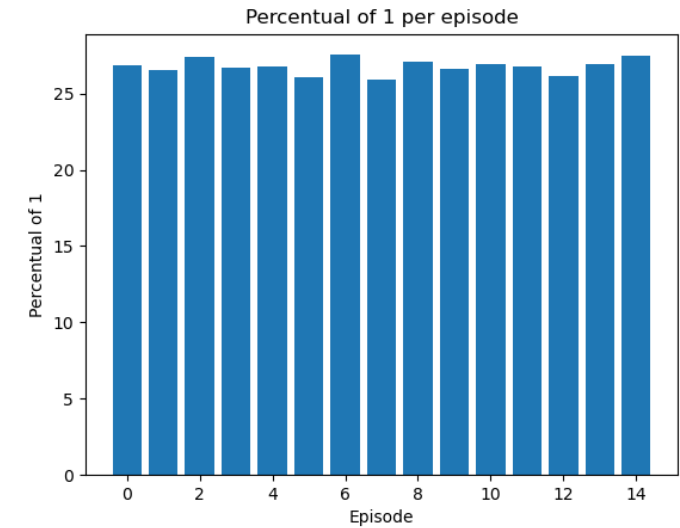
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	1.43	0.03	0.10	1.33, 1.53	7.14%
Machine 2	2.66	0.17	0.24	2.42, 2.90	8.95%
Machine 3	3.59	0.21	0.26	3.33, 3.86	7.37%
Machine 4	4.67	0.29	0.31	4.36, 4.99	6.67%
Machine 5	5.85	0.30	0.32	5.53, 6.17	5.45%
Machine 6	8.70	0.47	0.40	8.30, 9.10	4.58%

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	26.91	6.84	1.52	25.39, 28.42	5.64%



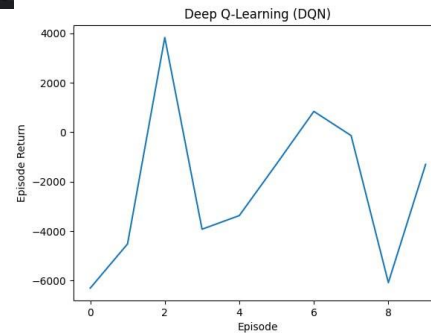
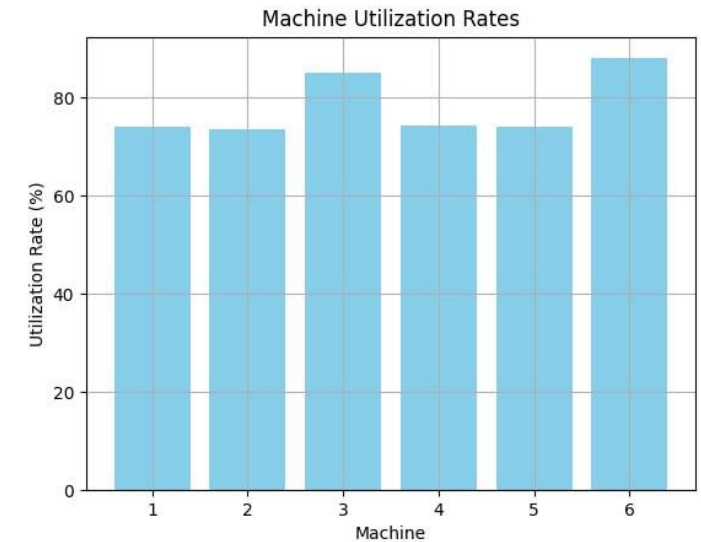
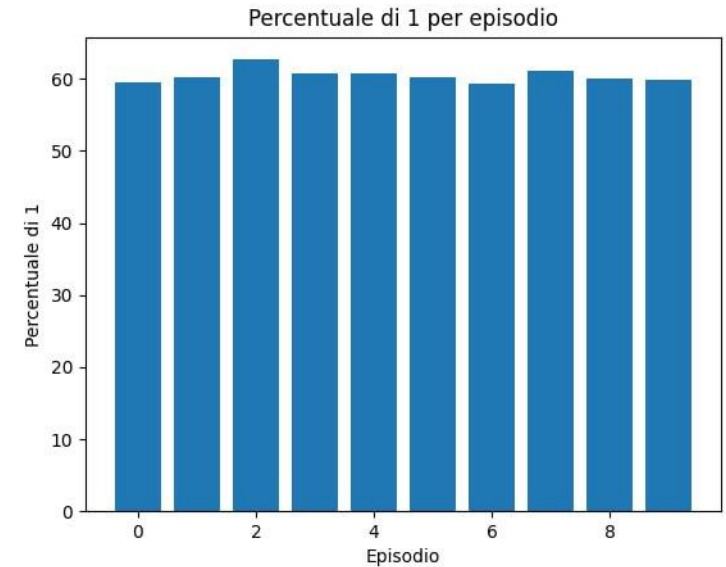
PPO – time_step_length 1,0

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	8.00	0.02	0.06	7.93, 8.06	0.79%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	0.26	0.00	0.02	0.24, 0.28	7.07%
Machine 2	0.46	0.01	0.03	0.43, 0.50	7.47%
Machine 3	0.54	0.00	0.03	0.51, 0.57	5.45%
Machine 4	0.73	0.01	0.04	0.70, 0.77	4.88%
Machine 5	0.91	0.01	0.05	0.85, 0.96	5.91%
Machine 6	1.27	0.03	0.08	1.19, 1.35	6.46%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	4.17	0.27	0.24	3.94, 4.41	5.66%



DQN – time_step_length 1,0

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	18.15	0.12	0.20	17.95, 18.35	1.09%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	3.29	0.07	0.15	3.14, 3.44	4.55%
Machine 2	5.72	0.19	0.25	5.47, 5.97	4.37%
Machine 3	9.88	0.38	0.36	9.52, 10.24	3.62%
Machine 4	10.55	0.70	0.49	10.06, 11.04	4.61%
Machine 5	13.05	0.56	0.43	12.62, 13.49	3.32%
Machine 6	18.67	0.62	0.46	18.21, 19.13	2.45%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	61.17	10.01	1.83	59.34, 63.00	3.00%

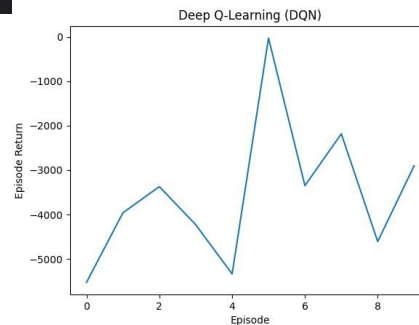
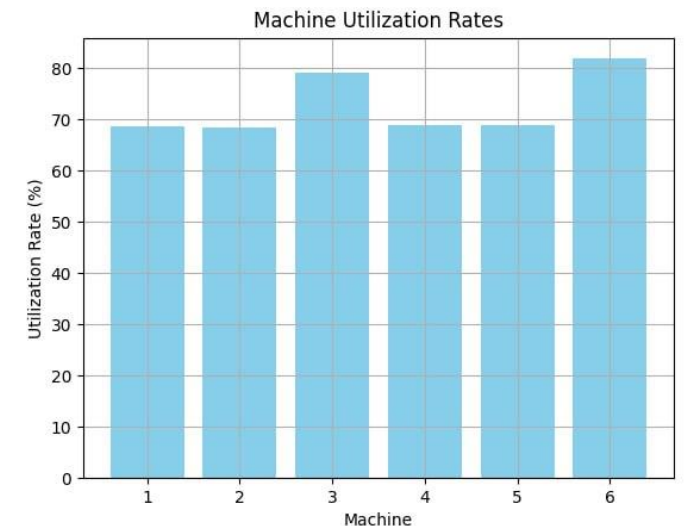
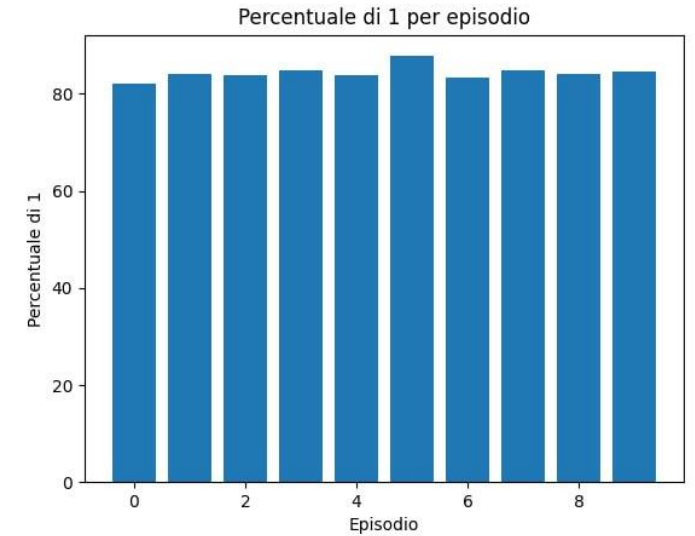


DQN – time_step_length 1,5

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	16.76	0.07	0.15	16.61, 16.91	0.89%

Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	1.35	0.01	0.06	1.29, 1.41	4.19%
Machine 2	2.49	0.02	0.08	2.41, 2.56	3.02%
Machine 3	4.07	0.06	0.15	3.92, 4.22	3.59%
Machine 4	4.81	0.08	0.16	4.65, 4.98	3.40%
Machine 5	6.06	0.09	0.18	5.89, 6.24	2.90%
Machine 6	9.37	0.17	0.24	9.14, 9.61	2.51%

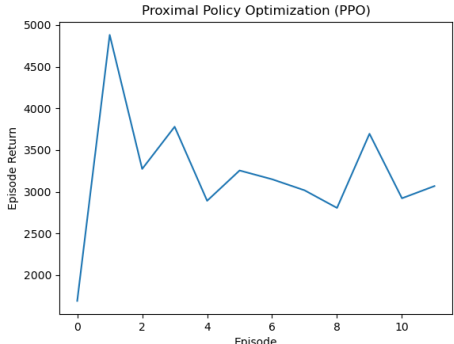
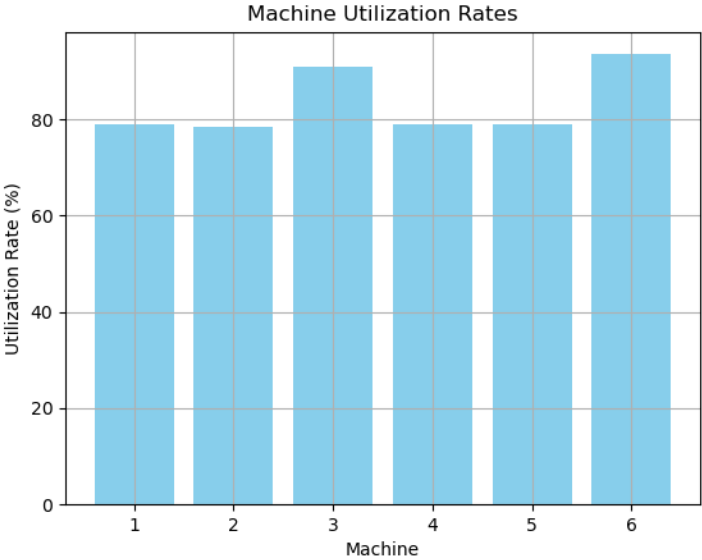
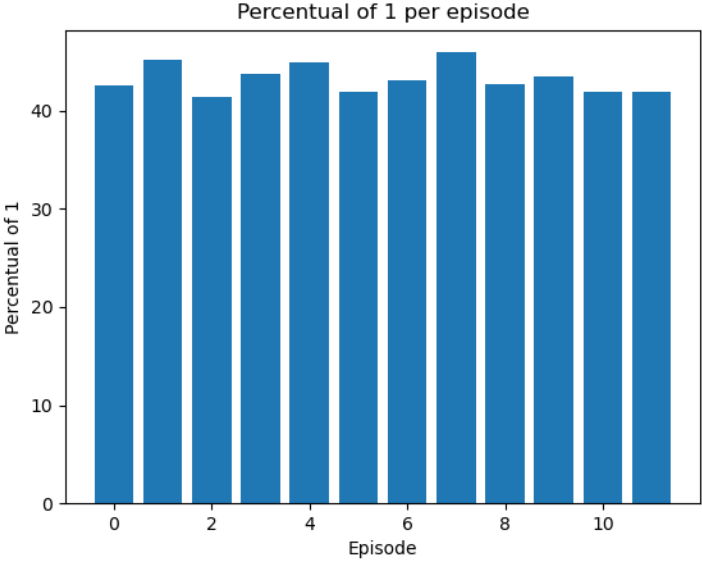
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	28.16	1.54	0.72	27.44, 28.88	2.55%



Simulations with different
clip_range (PPO algorithm)

PPO – clip_range 0,1

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	19.49	0.06	0.13	19.36, 19.62	0.66%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	6.17	2.90	0.88	5.28, 7.05	14.32%
Machine 2	10.73	7.70	1.44	9.30, 12.17	13.40%
Machine 3	30.60	114.31	5.54	25.06, 36.15	18.11%
Machine 4	27.41	62.32	4.09	23.32, 31.50	14.93%
Machine 5	30.58	61.28	4.06	26.52, 34.64	13.27%
Machine 6	57.93	217.57	7.65	50.29, 65.58	13.20%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	163.43	1806.29	22.03	141.40, 185.46	13.48%

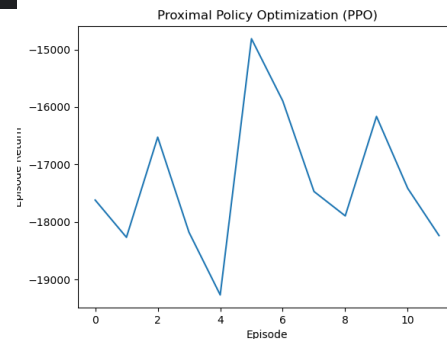
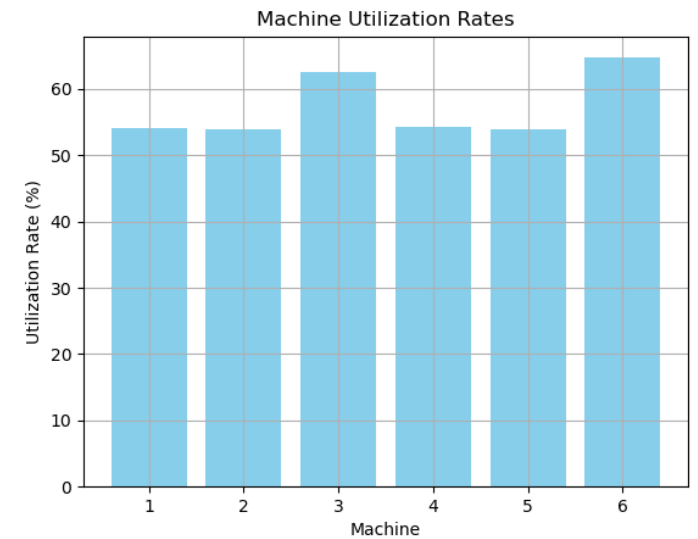
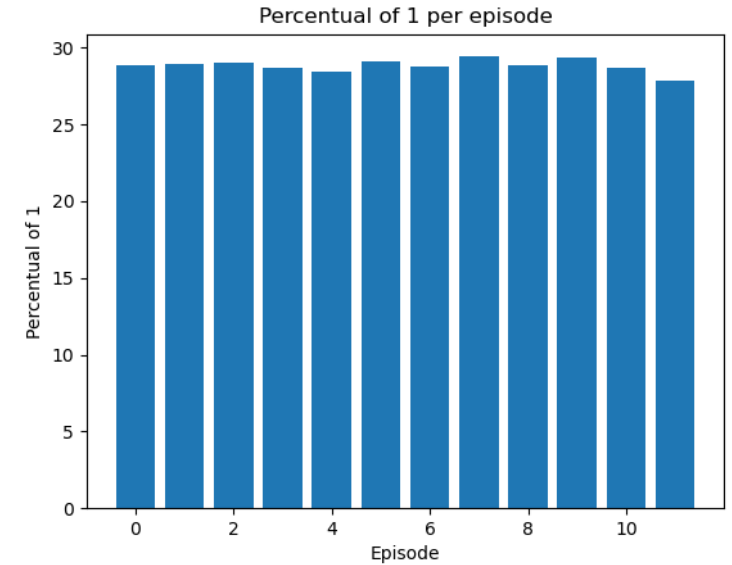


PPO – clip_range 0,3

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	13.36	0.04	0.10	13.26, 13.46	0.75%

Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	0.91	0.02	0.06	0.85, 0.98	7.01%
Machine 2	1.61	0.05	0.12	1.49, 1.73	7.31%
Machine 3	2.10	0.03	0.09	2.01, 2.20	4.51%
Machine 4	2.72	0.09	0.16	2.57, 2.88	5.73%
Machine 5	3.37	0.16	0.21	3.16, 3.58	6.17%
Machine 6	4.84	0.28	0.27	4.57, 5.11	5.64%

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	15.56	2.67	0.85	14.71, 16.41	5.44%



PPO – clip_range 0,4

-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Throughput	2.66	0.02	0.06	2.60, 2.73	2.42%
Machine	Mean	Variance	Half Interval	Confidence Interval	Relative Error
Machine 1	0.02	0.00	0.00	0.01, 0.02	18.15%
Machine 2	0.04	0.00	0.00	0.03, 0.04	12.71%
Machine 3	0.05	0.00	0.01	0.04, 0.05	11.25%
Machine 4	0.06	0.00	0.01	0.06, 0.07	11.09%
Machine 5	0.07	0.00	0.01	0.06, 0.08	15.63%
Machine 6	0.11	0.00	0.01	0.10, 0.12	11.98%
-	Mean	Variance	Half Interval	Confidence Interval	Relative Error
System wip	0.35	0.00	0.04	0.31, 0.38	10.34%

